MS - 4

$$I_{MS} = A_D A T^2 \exp\left(-\frac{q\Phi_B}{k_B T}\right);$$

$$I_{SM} \propto n(0); \qquad n(0) = N_C \exp\left(\frac{E_F - E_C(0)}{k_B T}\right) = N_C \exp\left(-\frac{q\Phi_B}{k_B T}\right);$$

$$n(\infty) = N_C \exp\left(\frac{E_F - E_C(\infty)}{k_B T}\right) \longrightarrow N_C = N_D \exp\left(\frac{E_C(\infty) - E_F}{k_B T}\right)$$

$$\hookrightarrow n(0) = N_D \exp\left(\frac{E_C(\infty) - E_F - q\Phi_B}{k_B T}\right) = N_D \exp\left(-\frac{qV_{bi}}{k_B T}\right) = N_D \exp\left(-\frac{V_{bi}}{V_T}\right);$$

$$\hookrightarrow n(0) \propto N_D \exp\left(-\frac{V_{bi} - V_a}{V_T}\right); \qquad n'(0) = n(0) - \ldots =$$

$$= N_D \exp\left(-\frac{V_{bi}}{V_T}\right)\left[\exp\left(\frac{V_a}{V_T}\right) - 1\right]$$

Alternativa: usare modello drift-diff:

$$J_n = q n \mu_n \mathcal{E} + q D_n \frac{\partial n}{\partial x};$$

Considero $\mathcal{E}$ come: $\mathcal{E} = -\frac{\partial E_C}{\partial x}$

$$\hookrightarrow J_n = +q\left[n\mu_n \frac{\partial E_C}{\partial x} + D_n \frac{\partial n}{\partial x}\right] = q D_n \left[\frac{n}{k_B T}\frac{\partial E_C}{\partial x} + \frac{\partial n}{\partial x}\right];$$

$$\hookrightarrow \int_0^{W_D} J_n \exp\left(\frac{E_C(x)}{k_B T}\right) dx = q D_n \left[n(x) \exp\left(\frac{E_C(x)}{k_B T}\right)\right]\Bigg|_0^{W_D}$$

dove: $E_C(0) = q\Phi_B$; $E_C(\infty) = q(\Phi_n + V_a)$;

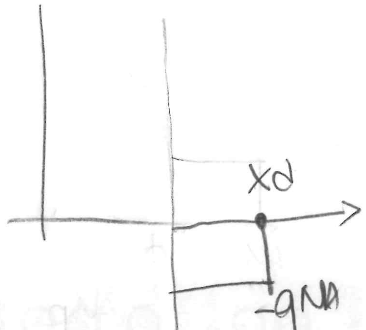
$$n(0) = N_C \exp\left(-\frac{q\Phi_B}{k_B T}\right); \qquad n(\infty) = N_C \exp\left(-\frac{q\Phi_n}{k_B T}\right);$$

sostituisco e trovo:

$$J_n = \frac{q N_C D_n \left[\exp\left(\frac{V_a}{V_T}\right) - 1\right]}{\int_0^{W_D} \exp\left(\frac{E_C(x)}{k_B T}\right) dx} \qquad E_C(x) = q\Phi_B - \frac{q^2 N_D}{\varepsilon_s}\left[x W_D - \frac{x^2}{2}\right]$$

MOS-2

$\longrightarrow$



$$\mathcal{E}(x) = -\frac{qN_A}{\varepsilon_s}\left[x - x_d\right] = \frac{qN_A}{\varepsilon_s}\left[x_d - x\right];$$

$$\varphi(x) = \frac{qN_A}{2\varepsilon_s}\left[x - x_d\right]^2 ; \quad \varphi(\phi) = \frac{qN_A}{2\varepsilon_s} x_d^2 .$$

$$\mathcal{E}(\phi^-) = +\frac{qN_A}{\varepsilon_{ox}} x_d ; \quad \varphi(t_{ox}) = \frac{qN_A}{\varepsilon_{ox}} x_d t_{ox} ;$$

$$\Phi_{bi} = \frac{qN_A}{2\varepsilon_s} x_d^2 + \frac{qN_A}{\varepsilon_{ox}} t_{ox} x_d \longrightarrow x_d^2 + \frac{2\varepsilon_s}{\varepsilon_{ox}} t_{ox} x_d - \frac{2\varepsilon_s}{qN_A}\Phi_{bi} = \phi$$

$$\hookrightarrow \boxed{-\frac{\varepsilon_s}{\varepsilon_{ox}} \pm \sqrt{\left(\frac{\varepsilon_s}{\varepsilon_{ox}} t_{ox}\right)^2 + \frac{2\varepsilon_s}{qN_A}\Phi_{bi}}}$$

JFET-1

$$Q_n = -qN_D\left[a - x_d\right], \quad x_d = [\text{Schottky}] = \sqrt{\frac{2\varepsilon_s}{qN_D}\left(\Phi_{bi} + \phi_{ch} - V_G\right)} .$$

$$= -qN_D a\left[1 - \frac{x_d}{a}\right] = -qN_D a\left[1 - \sqrt{\frac{2\varepsilon_s\left(\Phi_{bi} + \phi_{ch} - V_G\right)}{qN_D a^2}}\right]$$

$$Q_n = \phi \Rightarrow V_{bi} + \cancel{V_{DS}} - V_{GS} = \frac{qN_D}{2\varepsilon_s} a^2 \longrightarrow V_{GS}\big|_{ord} = \frac{qN_D}{2\varepsilon_s} a^2 - V_{bi}$$

$$\rightarrow V_{th} = V_{bi} - \frac{qN_D}{2\varepsilon_s} a^2 ; \quad -\left(V_{th} - V_{bi}\right) = \frac{qN_D}{2\varepsilon_s} a^2$$

$$\hookrightarrow -qN_D a\left[1 - \sqrt{\frac{V_{bi} - \left(V_{GS} - \phi_{ch}\right)}{V_{bi} - V_{th}}}\right] = -qN_D a\left[1 - \sqrt{1 - \frac{V_{GS} - \left(\phi_{ch} + V_{th}\right)}{V_{bi} - V_{th}}}\right].$$

So che:

$$\frac{d^2\varphi}{dx^2} = -\frac{\rho(x)}{\varepsilon_s} \Longrightarrow \rho(x) = q\left[p_p(x) - n_p(x) - N_A^- + \cancel{N_D^+}\right];$$

So che: $p_p(x) = n_i \exp\left(\frac{E_{Fi}(x) - E_F}{k_BT}\right)$; $n_p(x) = n_i \exp\left(\frac{E_F - E_{Fi}(x)}{k_BT}\right)$;

definisco $q\varphi(x) = E_F - E_{Fi}(x) \Longrightarrow p(x) = n_i \exp\left(-\frac{q\varphi(x)}{V_T}\right)$;

$$n(x) = n_i \exp\left(\frac{q\varphi(x)}{V_T}\right);$$

Per $x \to \infty$, $p_p(x) = N_A = n_i \exp\left(\frac{E_F - E_{Fi}(\infty)}{k_BT}\right) = n_i \exp\left(\frac{q\phi_p}{k_BT}\right)$;

$$n_p(x) = \frac{n_i^2}{N_A} = n_i \exp\left(-\frac{q\phi_p}{k_BT}\right);$$

$n_i = n_{p0} \exp\left(+\frac{q\phi_p}{k_BT}\right)$; $n_i = p_{p0} \exp\left(-\frac{q\phi_p}{k_BT}\right)$;

$\hookrightarrow p_p(x) = p_{p0} \exp\left(-q\frac{\varphi(x) - \phi_p}{k_BT}\right)$; $n_p(x) = n_{p0} \exp\left(-q\frac{\phi_p - \varphi(x)}{k_BT}\right)$;

definisco: $\psi(x) \triangleq \frac{q(\varphi(x) - \phi_p)}{-q}$

$\longrightarrow p_p(x) = p_{p0} \exp\left(\frac{\psi(x)}{V_T}\right)$; $n_p(x) = n_{p0} \exp\left(\frac{\psi(x)}{V_T}\right)$;

Ma: @ ∞, ho <u>neutralità</u>!

$$p_{p0} - n_{p0} - N_A^- = 0 \Rightarrow N_A^- = p_{p0} - n_{p0}$$

$$\hookrightarrow \frac{d^2\varphi}{dx^2} = \frac{q}{\varepsilon_s}\left[p_{p0}\left[\exp\left(\frac{\psi(x)}{V_T}\right) - 1\right] - n_{p0}\left[\exp\left(-\frac{\psi(x)}{V_T}\right) - 1\right]\right]$$

05/02/04 - compito A

2) Usando il formulario, vedo che:

$$\beta_F = 150 = \frac{\alpha_F}{1-\alpha_F} \longrightarrow \left(\frac{1}{\alpha_F}-1\right)\times 150 = 1 \longrightarrow \alpha_F = \left(\frac{1}{150}+1\right)^{-1} = \frac{150}{151} = 0{,}99334;$$

$$\alpha_F = b\,\gamma_F = \left(1-\frac{W_B^2}{2L_{nB}^2}\right)\left(1+\frac{N_B W_B D_{pE}}{N_E W_E D_{nB}}\right)^{-1}.$$

Dove, calcoli mi danno: $\left\{ \begin{array}{l} D_{pE} = 5{,}2; \\ D_{nB} = 20{,}8; \\ L_{nB} = 1{,}442\,E\text{-}3. \end{array} \right\}$ tutto riferito a cm!

Questa è un'equazione; per la seconda ricordo che:

$$A_E = 1\,\mu m^2 = 1E4\ \mu m/cm\ (\mu cm\ \text{lo sbaglio}) = 1E\text{-}2\ cm^2;$$

Ricordo che, infine, la legge di Ohm afferma:

$$R_E = \rho_E \frac{W_E}{A_E} = \frac{1}{N_E \mu_{nE} q}\cdot\frac{W_E}{A_E} \le 1\,\Omega. \Longrightarrow \boxed{\frac{W_E}{N_E} \le q\,\mu_{nE} A_E.}$$

$$\hookrightarrow \alpha_F = \left(1-\frac{W_B^2}{2L_{nB}^2}\right)\left(1+\frac{N_B W_B D_{pE}}{q\,\mu_{nE} A_E N_E^2 D_{nB}}\right)^{-1} = \frac{150}{151}$$

Terza "implicata" condizione: essendo un BJT, $N_E \gg N_B$. Come parametro libero scelgo proprio $N_E = 5\,E\,17$ (10 volte N_B), e da qui posso calcolare, mediante calcolatrice, W_B:

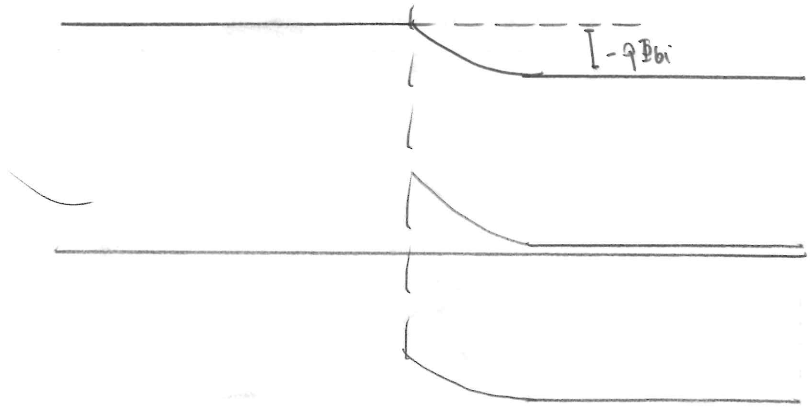
$W_B = 1{,}6\ \mu m;$

$W_E = 0{,}560\ cm \rightarrow 5{,}6\ mm$ (mi sembra tanto).

5/2/04 - compito B

(22)

2) Non chiedendo nulla fingo che sul formulario non ci sia e parto da:



$$x_d = \sqrt{\frac{2\varepsilon_s}{qN_D}(V_{bi}-V)}$$

$$V_{bi} = q\Phi_M - q\Phi_{sn} =$$

$$= q\Phi_M - \left(q\chi_s + \frac{E_g}{2} - (E_F - E_{Fi})\right) =$$

$$= q\Phi_M - \left(q\chi_s + \frac{E_g}{2} - k_BT\ln\left(\frac{N_D}{n_i}\right)\right) =$$

$$= q\Phi_M - q\chi_s - \frac{E_g}{2} + k_BT\ln\left(\frac{N_D}{n_i}\right) = 1{,}051\ eV$$

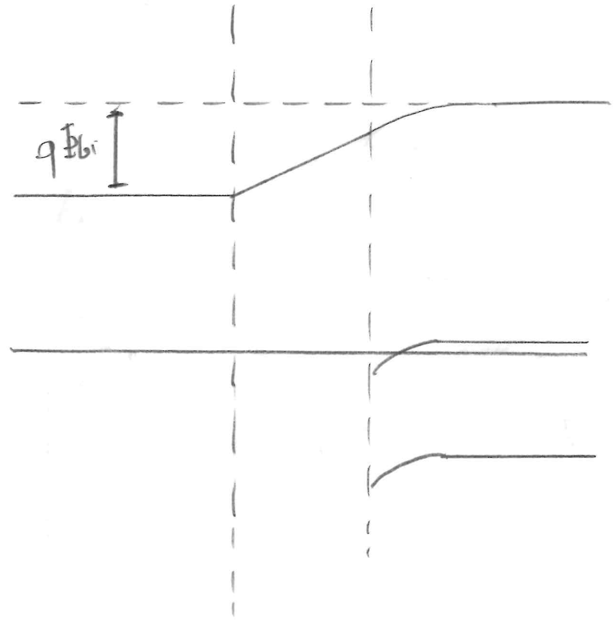
$$Q_d = +qN_D x_d = \sqrt{2qN_D\varepsilon_s(V_{bi}-V)};$$

$$C_d = A\left|\frac{dQ_d}{dC_d}\right| = \frac{1}{\cancel{2}}\frac{+\cancel{2}qN_D\varepsilon_s}{\sqrt{2qN_D\varepsilon_s(V_{bi}-V)}} = \frac{1}{2}\sqrt{\frac{2qN_D\varepsilon_s}{V_{bi}-V}} = \sqrt{\frac{qN_D\varepsilon_s}{2(V_{bi}-V)}}$$

$V_{bi} = 1{,}051\ V$;

$C_d = 2{,}643\ pF$ =

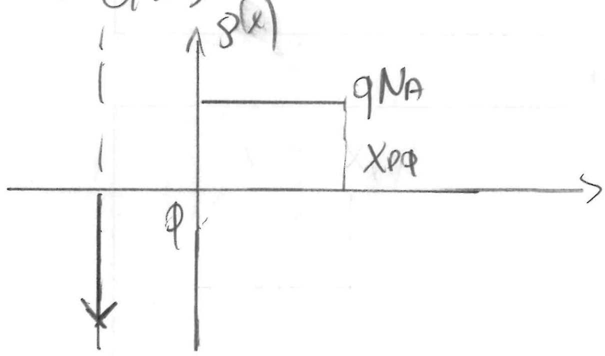
Giunzione MS



$$q\Phi_{bi} = q\Phi_M - q\Phi_{S_n} = q\Phi_M - \left(q\chi_s + \frac{E_g}{2} + (E_{Fi} - E_F)\right)$$

$$= q\Phi_M - q\chi_s - \frac{E_g}{2} - K_BT\ln\left(\frac{N_A}{n_i}\right) =$$

$$= -0{,}8595$$



$$\mathcal{E}(x) = \int \frac{\rho(x)}{\varepsilon_s}\,dx = \frac{qN_A}{\varepsilon_s}x + c \;;$$

$$\frac{qN_A}{\varepsilon_s}x_{p0} + c = 0$$

$$\hookrightarrow \mathcal{E}(x) = \frac{qN_A}{\varepsilon_s}\left[x - x_{p0}\right] \;; \quad (x > 0)$$

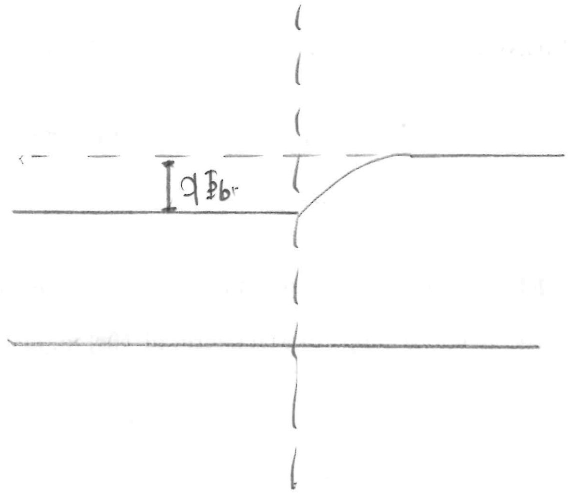
$$\varphi(x) = -\int \mathcal{E}(x)\,dx = -\frac{qN_A}{2\varepsilon_s}\left[x - x_{p0}\right]^2 + c\;;$$

@ $x = x_{p0}$, $\varphi(x) = 0 \Rightarrow c = 0$!

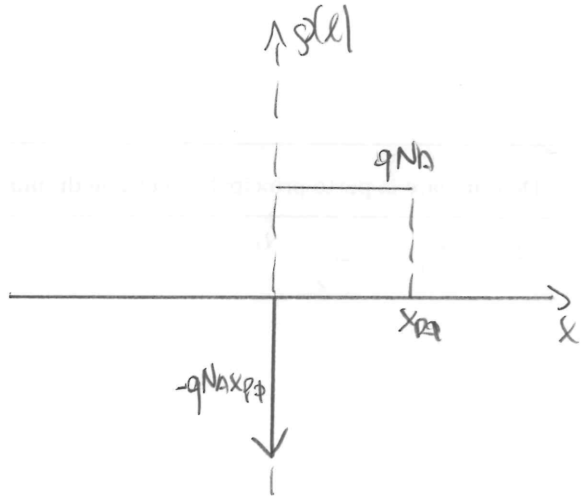
$-t_{ox} < x < 0$, $\mathcal{E}(x) =$ costante ;

$$\mathcal{E}(0^-) = \mathcal{E}(0^+)\frac{\varepsilon_s}{\varepsilon_{ox}} = -\frac{qN_A}{\varepsilon_{ox}}x_{p0} \;;$$

Sistema MOS



$q\Phi_{bi} = -0{,}8595$ eV.



$$\mathcal{E}(x) = \frac{qN_A}{\varepsilon_s}\left[x - x_{p0}\right] \quad (x \geq 0)\;;$$

$$\varphi(x) = -\frac{qN_A}{2\varepsilon_s}\left[x - x_{p0}\right]^2 \;;$$

$$\hookrightarrow \Phi_i = \varphi(0) = -\frac{qN_A}{2\varepsilon_s}x_{p0}^2 \;;$$

$$\varphi(x) = \int \frac{qN_A}{\varepsilon_{ox}} x_{p\phi} = \frac{qN_A}{\varepsilon_{ox}} x_{p\phi}\, x + c;$$

(ignoro "c" e faccio in modo da avere:

$$\varphi(t_{ox}) = \frac{qN_A}{\varepsilon_{ox}} x_{p\phi}\, t_{ox};$$

$$\Phi_{bi} = \frac{qN_A}{\varepsilon_{ox}} x_{p\phi}\, t_{ox} - \frac{qN_A}{2\varepsilon_s} x_{p\phi}^2$$

↳ $x_{p\phi}^2 - 2\frac{\varepsilon_s}{\varepsilon_{ox}} t_{ox}\, x_{p\phi} - \frac{2\varepsilon_s}{qN_A}\Phi_{bi} = 0$

↳ $\frac{\varepsilon_s}{\varepsilon_{ox}} t_{ox} \pm \sqrt{\left(\frac{\varepsilon_s}{\varepsilon_{ox}} t_{ox}\right)^2 + \frac{2\varepsilon_s}{qN_A}\Phi_{bi}}$

$$Q_d = qN_A x_p = \frac{1}{2}\,\frac{\frac{2\varepsilon_s}{qN_A}}{\sqrt{\left(\frac{\varepsilon_s}{\varepsilon_{ox}} t_{ox}\right)^2 + \frac{2\varepsilon_s}{qN_A}(\Phi_{bi} - V_a)}}$$

$= 11,78\ \mu F/cm^2$;

$C_{ox} = \frac{\varepsilon_{ox}}{t_{ox}} = 67,29\ nF/cm^2$

→ prendo la minore

↳ $C = 66,91\ nF/cm^2$!

↳ $x_{p\phi} = \pm\sqrt{\frac{2\varepsilon_s}{qN_A}\Phi_i}$

↳ $qN_A x_{p\phi} = \sqrt{2qN_A\varepsilon_s(\Phi_i - V_a)}$;

$$\frac{dQ}{dV_a} = -\frac{1}{2}\,\frac{-q2N_A\varepsilon_s}{\sqrt{2qN_A\varepsilon_s(\Phi_i - V_a)}} = \sqrt{\frac{qN_A\varepsilon_s}{2(\Phi_i - V_a)}}$$

↳ $C_{MS} = 19,59\ nF/cm^2$!

Valutare tensione di soglia della struttura MOS.

Si ha, dal formulario:

$V_{th} = V_{th\phi} + \cancel{\gamma B} \ldots$

dove:

$V_{th\phi} = V_{FB} + 2\phi_p + \cancel{\gamma B} \ldots$

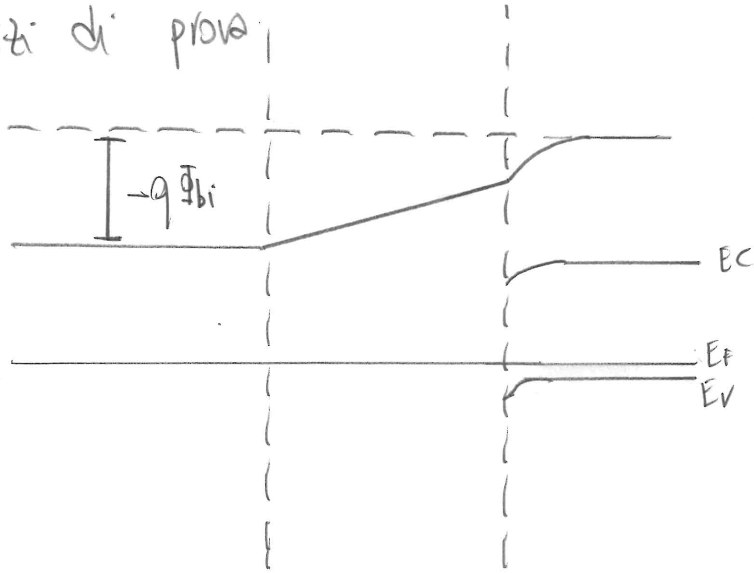
e

$q\phi_p = E_{Fi} - E_F = qV_T \ln\frac{N_A}{n_i} = 0,3495\ eV$;

$V_{th\phi} = V_{th} = 2\phi_p + V_{FB} = \underline{1,559\ V}$

Esercizi di prova

1) a)



$$q\Phi_{bi} = q\Phi_M - q\Phi_S =$$
$$= \cancel{q\chi_s} - \left(\cancel{q\chi_s} + \frac{E_g}{2} + (E_{Fi} - E_F)\right)$$
$$= -K_BT\ln\left(\frac{N_A}{n_i}\right) - \frac{E_g}{2} =$$
$$= \boxed{-0{,}91\,eV.}$$

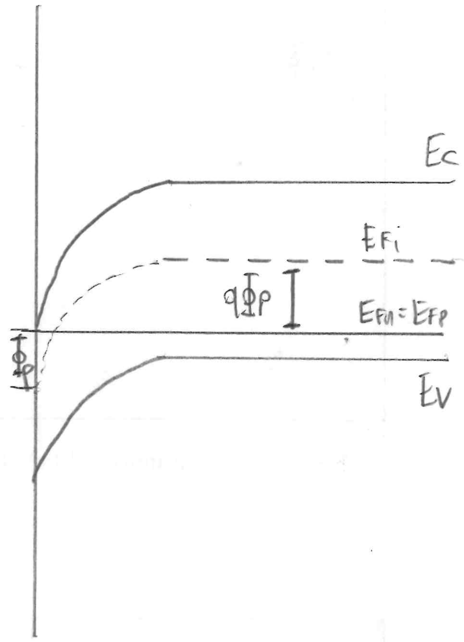
$\hookrightarrow V_{FB} = -0{,}91\ V.$

Dal formulario; ricordando che V_{FB} è la tensione applicata dall'esterno che porta il livello del vuoto a esser costante. Il "+" sta sul metallo, SEMPRE.

$-q\phi_P = 0{,}3495\ eV.$

b) $\hookrightarrow V_{th} = V_{th0}$ (no body) $= 1{,}609\ V$!

c) Il quesito chiede sostanzialmente un diagramma a bande in forte inversione. In questo stato, i livelli sono molto incurvati;



$E_{Fi}(\phi) - E_{Fi}(\infty) = -2\,\phi_P$, e rimane circa bloccato a ciò.

d) $Q_n = -C_{ox}(V_{GS} - \cancel{\phi_{ch}} - V_{th}) = \boxed{-\frac{\varepsilon_{ox}}{t_{ox}}(V_{GS} - V_{th})} = -93{,}6\ nC$ (inversione).

$Q_d = +qN_A\,x_d(3V) =$

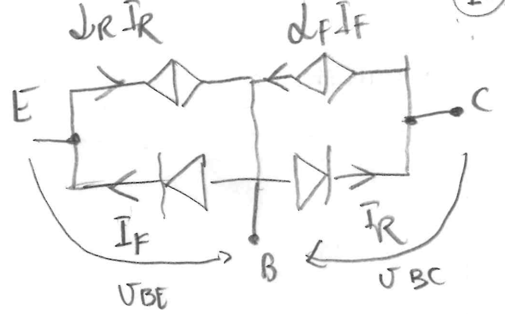
e) $Q_n = -C_{ox}(V_{GS} - \phi_{ch}(y) - V_{th})$; $\phi_{ch}(y) =$ retta che cresce da ϕ a $0{,}5\,V$ su L.

$$\frac{y-0}{0{,}5-0} = \frac{x-\phi}{L-\phi} \Longrightarrow \boxed{y = \frac{x}{L}\cdot 0{,}5} \Longrightarrow \boxed{\phi_{ch}(y) = \frac{y}{L}\cdot 0{,}5}$$

$y = \phi$ è il source.

Esercizio 2

Considero il modello del formulario (iniezione):



$$\begin{cases} I_E = \alpha_R I_R - I_F ; \\ I_C = \alpha_F I_F - I_R ; \end{cases} \qquad \begin{cases} I_F = I_{ES}\left[\exp\left(\frac{v_{BE}}{V_T}\right)-1\right] \\ I_R = I_{CS}\left[\exp\left(\frac{v_{BC}}{V_T}\right)-1\right] \end{cases}$$

Valutare: α_R, α_F, I_{CS} e I_{ES}. Si sa che: $I_C = 3\,nA$, E aperto; $30\,nA$, E in cc con base; $450\,nA$, base aperta.
$v_{BC} < \phi$.

1) Ricordo che: $\boxed{\alpha_F I_{ES} = \alpha_R I_{CS}}$.

Se l'emettitore è aperto

$I_E = \alpha_R I_R - I_F = \phi \rightarrow$ dato che $v_{BC} < \phi$, $I_R \simeq -I_{CS}$.

$\hookrightarrow I_F = -\alpha_R I_{CS}$; $\longrightarrow I_C = \alpha_F I_F - I_R = -\alpha_F \alpha_R I_{CS} + I_{CS} = I_{CS}(1-\alpha_F\alpha_R)$.

2) $I_E = \alpha_R I_R - I_F$, ma $I_F = \phi$ ($v_{BE} = \phi$!)

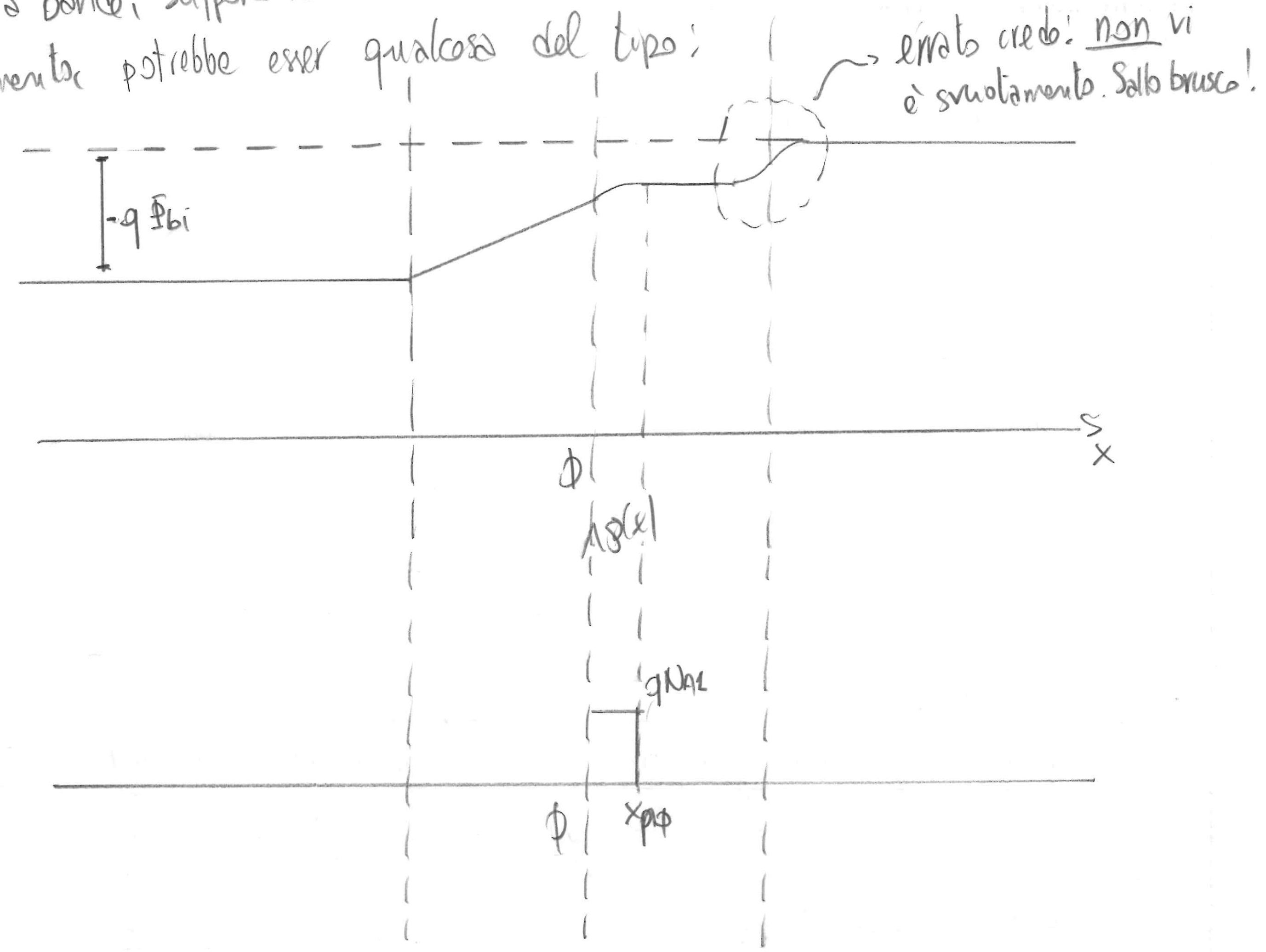
$\hookrightarrow I_C = -I_R = I_{CS}$.

3) $I_B = -I_C - I_E = I_F + I_R - \alpha_R I_R - \alpha_F I_F = I_F(1-\alpha_F) + I_R(1-\alpha_R) = \phi$;

$$I_F = -I_R \frac{1-\alpha_R}{1-\alpha_F} = I_{CS}\frac{1-\alpha_R}{1-\alpha_F}.$$

Risolvendo il sistema si trovano i parametri.

Il d. a bande, supponendo che non vi sia overlap delle regioni di svuotamento, potrebbe esser qualcosa del tipo:



$$\mathcal{E}(x) = \int \frac{qN_{A1}}{\varepsilon_s} dx = \frac{qN_{A1}}{\varepsilon_s}\left[x - x_{p\phi}\right]; \quad \varphi(x) = -\frac{qN_{A1}}{2\varepsilon_s}\left[x - x_{p\phi}\right]^2; \quad x>0$$

Vorrei vedere quanto si estende $x_{p\phi}$, e verificare l'ipotesi.

$\hookrightarrow \varphi(\phi^+) = -\frac{qN_{A1}}{2\varepsilon_s} x_{p\phi}^2;$

$\mathcal{E}(x) = -\frac{qN_{A1}}{\varepsilon_{ox}} x_{p\phi}$ (nell'ossido);

$\hookrightarrow \varphi(x) = \frac{qN_{A1}}{\varepsilon_{ox}} x_{p\phi}\, x \Longrightarrow \varphi(t_{ox}) = c + \frac{qN_{A1}}{\varepsilon_{ox}} x_{p\phi} t_{ox};$

$\hookrightarrow \varphi(t_{ox}) = -\frac{qN_{A1}}{2\varepsilon_s} x_{p\phi}^2 + \frac{qN_{A1}}{\varepsilon_{ox}} x_{p\phi} t_{ox} = \Phi_T$ (Φ_T è una "barriera" che non tien conto di N_{A2}).

$\hookrightarrow x_{p\phi}^2 - \frac{2\varepsilon_s}{\varepsilon_{ox}} t_{ox} x_{p\phi} + \Phi_T \frac{2\varepsilon_s}{qN_{A1}} = \phi \longrightarrow x_{p\phi} = \frac{\varepsilon_s}{\varepsilon_{ox}} t_{ox} \pm \sqrt{\left(\frac{\varepsilon_s}{\varepsilon_{ox}} t_{ox}\right)^2 - \frac{2\varepsilon_s}{qN_{A1}}\Phi_T}$

→ Calcolo Φ_t :

$$q(\Phi_M - \Phi_s) = \cancel{q\chi_s} - \left[\cancel{q\chi_s} + \frac{E_g}{2} + (E_{Fi} - E_F)\right] = -\frac{E_g}{2} - k_B T \ln\left(\frac{N_A}{n_i}\right) = -0,9\ eV$$

↳ $x_{pp} \perp 70\ nm$.

Cosa vuol dire? Che la regione di svuotamento attraversa <u>tutta</u> la regione svuotata.

$$V_s = \frac{qN_{A1}}{2\varepsilon_s} x_i^2 + \frac{qN_{A2}}{2\varepsilon_s}\left(x_d^2 - x_i^2\right) \Longrightarrow x_d = \sqrt{\frac{2\varepsilon_s}{qN_{A2}}\left[V_s - \frac{q}{2\varepsilon_s}(N_{A1} - N_{A2})x_i^2\right]}$$

@ soglia, $V_s = 2\Phi_p - \cancel{V_{BS}}$ (ignoro effetto body) (Φ_p definito rispetto a $\boxed{N_{A2}}$ (quello dove finisce la regione di svuotamento).

↳ $x_d \sqrt{\frac{2\varepsilon_s}{qN_{A2}}\left[2\Phi_p - \frac{q}{2\varepsilon_s}(N_{A1} - N_{A2})x_i^2\right]}$

$$Q_t = -Q_n - Q_d = -C_{ox}(V_{GS} - \phi_{ch} - 2\phi_p) - qN$$

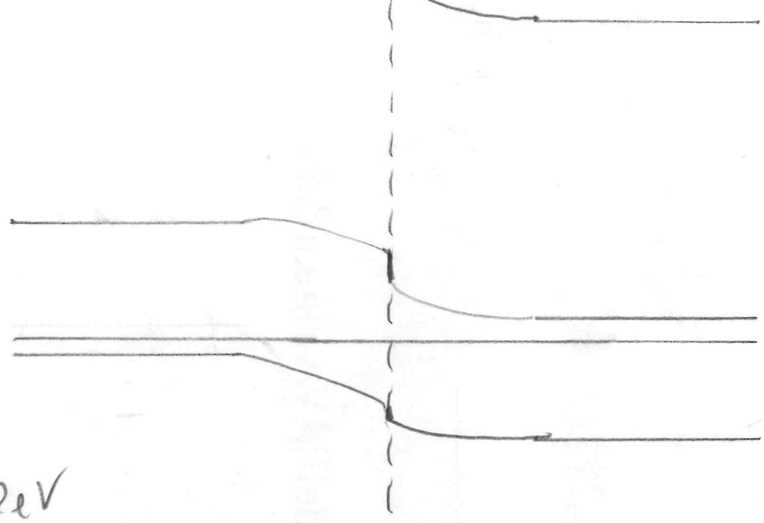
RIVEDERE

o

finire

23/01/2008

2) a)



$\Delta E_g = E_{g2} - E_{g1} = -0{,}225\ eV$;

$q\Delta\chi = q\chi_2 - q\chi_1 = 0{,}265\ eV$;

$q\Phi_{bi} = q\Phi_{s_2} - q\Phi_{s1} = q\chi_2 + (E_C - E_F) -$

$+ [q\chi_1 + E_{g1} - (E_F - E_V)]$

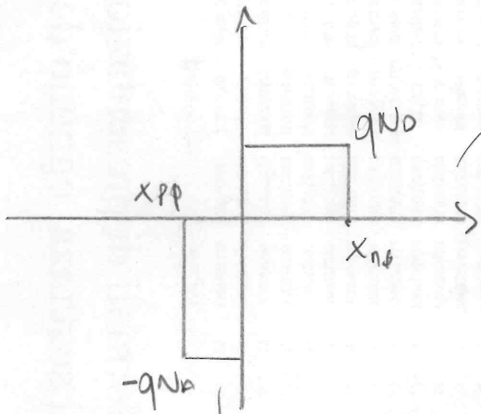
$= q\Delta\chi - E_{g1} + k_BT \ln\left(\frac{N_{C2} N_{V1}}{N_{D2} N_{A1}}\right) = -1{,}32\ eV$

Cerchiamo di capire come fa il diagr. a bande: $\Delta\chi > 0$, dunque $E_C(0^+) < E_C(0^-)$:

$\Delta E_C = E_{C2} - E_{C1} = -q\Delta\chi$; $\Delta E_C < 0 \Longrightarrow$ disc. di questo tipo.

$\Delta E_V = -q\Delta\chi - \Delta E_g = -0{,}04\ eV$.

b)



$\mathcal{E}(x) = \int \frac{qN_D}{\varepsilon_2} dx = \frac{qN_D}{\varepsilon_2}[x - x_{n0}]$;

$\varphi(x) = -\frac{qN_D}{2\varepsilon_2}[x - x_{n0}]^2$

↳ $\varphi(0) = -\frac{qN_D}{2\varepsilon_2} x_{n0}^2$;

$\mathcal{E}(x) = \int -\frac{qN_A}{\varepsilon_1} dx = -\frac{qN_A}{\varepsilon_1} x + C$; $-\frac{qN_A}{\varepsilon_1} x_{p0} = -C$

$\rightarrow \mathcal{E}(x) = \frac{qN_A}{\varepsilon_1}[x_{p0} - x]$

$\varphi(x) = \frac{qN_A}{2\varepsilon_1}[x - x_{p0}]^2$.

Nota: $\mathcal{D}(0^+) = \mathcal{D}(0^-)$:

$\rightarrow -\frac{qN_D}{\cancel{\varepsilon_2}}\cancel{\varepsilon_2} x_{n0} = \frac{qN_A}{\cancel{\varepsilon_1}}\cancel{\varepsilon_1} x_{p0}$ $[x_{p0} < 0!]$

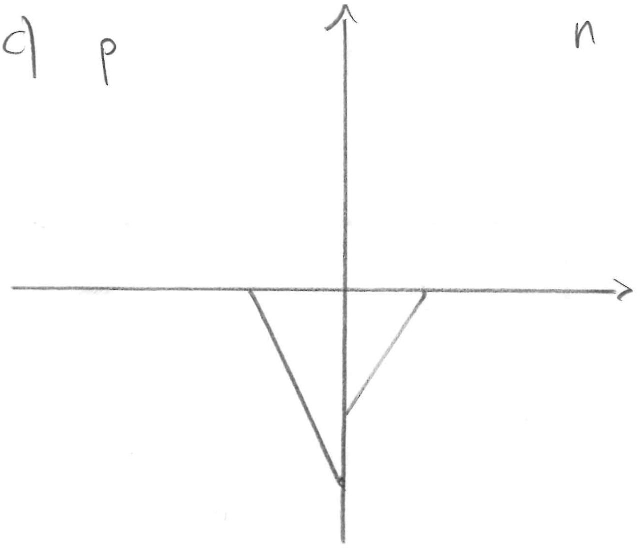
Poi: $\cancel{q}N_D x_{n0} = \cancel{q}N_A x_{p0}$! $x_{p0} = \frac{N_D}{N_A} x_{n0}$

$\Phi_{bi} = \frac{qN_{A1}}{2\varepsilon_1} x_{p0}^2 + \frac{qN_{D2}}{2\varepsilon_2} x_{n0}^2 = \frac{q\cancel{N_{A1}}}{2\varepsilon_1}\frac{N_D^2}{N_A^2} x_{n0}^2 + \frac{qN_{D2}}{2\varepsilon_2} x_{n0}^2 = \frac{qN_{D2}}{2}\left[\frac{N_D}{\varepsilon_1 N_A} + \frac{1}{\varepsilon_2}\right] x_{n0}^2$.

$\rightarrow = \frac{qN_{D2}}{2}\left[\frac{\varepsilon_2 N_{D2} + \varepsilon_1 N_{A1}}{\varepsilon_1 N_A \varepsilon_2}\right] x_{n0}^2 \longrightarrow x_{n0} = \sqrt{\frac{2}{qN_{D2}}\frac{\varepsilon_1 N_A \varepsilon_2}{\varepsilon_2 N_{D2} + \varepsilon_1 N_{A1}}\Phi_i} =$

$= \sqrt{\frac{2}{qN_{D2}^2}\frac{\varepsilon_1 N_{A1}\varepsilon_2 N_{D2}}{\varepsilon_2 N_{D2} + \varepsilon_1 N_{A1}}\Phi_i}$

c) p n



$$\mathcal{D}(0^-) = \mathcal{D}(0^+)$$

$$\hookrightarrow \varepsilon_1 \mathcal{E}(0^-) = \varepsilon_2 \mathcal{E}(0^+)$$

minore è ε_1 maggiore è $\mathcal{E}$!

$\hookrightarrow$ maggiore in (1).

$$\mathcal{E}(0^-) = \frac{q N_A}{\varepsilon_1} x_{p0}.$$

d) Per far ciò, servono le leggi della giunzione. Le ricavo, per l'occasione, perché a memoria non lo so.

$$p_n(x_n) n_p(x_p) = [\text{da formulario}] = N_{V2} \exp\left(\frac{E_V(x_n) - E_F}{k_B T}\right) N_{C1} \exp\left(\frac{E_F - E_C(x_p)}{k_B T}\right)$$

Per ora, @ eq. th. $\hookrightarrow = N_{C1} N_{V2} \exp\left(\frac{E_V(x_n) - E_C(x_p)}{k_B T}\right)$ ma $\begin{cases} E_C(x_p) - E_V(x_n) = \Delta E_C + E_{g2} = \\ \Delta E_V + E_{g1} \end{cases}$

Poi:

$$p_n(x_n) n_n(x_n) \cong N_{D2} p_n(x_n) = N_{V2} \exp\left(\frac{E_V(x_n) - E_F}{k_B T}\right) N_{C2} \exp\left(\frac{E_F - E_C(x_n)}{k_B T}\right) = N_{V2} N_{C2} \exp\left(-\frac{E_{g2} + q\Phi_{bi}}{k_B T}\right)$$

$$\hookrightarrow p_n(x_n) = \frac{N_{V2} N_{C2}}{N_{D2}} \exp\left(-\frac{E_{g2}}{k_B T}\right).$$

Dunque, riscrivo l'exp come:

$$n_p(x_p) = \frac{N_{D2}}{\cancel{N_{V2}} N_{C2}} \cancel{N_{V2}} N_{C1} \cancel{\exp\left(\frac{E_{g2}}{k_B T}\right)} \exp\left(-\frac{\cancel{E_{g2}} + \Delta E_C}{k_B T}\right) = \frac{N_{C1}}{N_{C2}} N_{D2} \exp\left(-\frac{q\Phi_{bi} + \Delta E_C}{k_B T}\right).$$

Allo stesso modo si tira fuori:

$$p_n(x_n) = \frac{N_{V2}}{N_{V1}} N_{A1} \exp\left(-\frac{q\Phi_{bi} + \Delta E_V}{k_B T}\right).$$

$$\hookrightarrow n_p'(x_p) = \frac{N_{C1}}{N_{C2}} N_{D2} \exp\left(-\frac{\Delta E_C + q\Phi_{bi}}{k_B T}\right) \left[\exp\left(\frac{V_a}{V_T}\right) - 1\right].$$

$$p_n'(x_n) = \frac{N_{V2}}{N_{V1}} N_{A1} \exp\left(-\frac{\Delta E_V + q\Phi_{bi}}{k_B T}\right) \left[\exp\left(\frac{V_a}{V_T}\right) - 1\right];$$

e) Pongo $n_p'(x_p) = p_n'(x_n)$:

$$\frac{N_{C1}}{N_{C2}} N_{D2} \exp\left(-\frac{\Delta E_C}{K_B T}\right) = \frac{N_{V2}}{N_{V1}} N_{A2} \exp\left(-\frac{\Delta E_V}{K_B T}\right).$$

$$\hookrightarrow N_{D2} = N_{A2} \frac{N_{V2} N_{C2}}{N_{V1} N_{C1}} \exp\left(-\frac{\Delta E_V - \Delta E_C}{K_B T}\right).$$

Cosa capita in una omogiunzione? Consideriamo, dal formulario, le tradizionali leggi della giunzione:

$$n_p(x_p) = n_{p\phi}(x_p)\left[\exp\left(\frac{V_d}{V_T}\right)-1\right]; \quad p_n(x_n) = p_{n\phi}(x_n)\left[\exp\left(\frac{V_d}{V_T}\right)-1\right]$$

Queste si potevano ottenere considerando che $N_{V2} = N_{V1}$, $N_{C2} = N_{C1}$, $\Delta E_V = \Delta E_C = \phi$, e facendo "degenerare" le leggi della giunzione generalizzata.

$$n_p(x_p) = p_n(x_n) \Longrightarrow n_{p\phi}(x_p) = p_{n\phi}(x_n)$$

che è quello che si ottiene degenerando le equazioni.

Faccio un po' di conti:

b) $x_{n\phi} = 257$ nm; $x_{p\phi} = x_{n\phi} \frac{N_D}{N_A} = 1028$ nm;

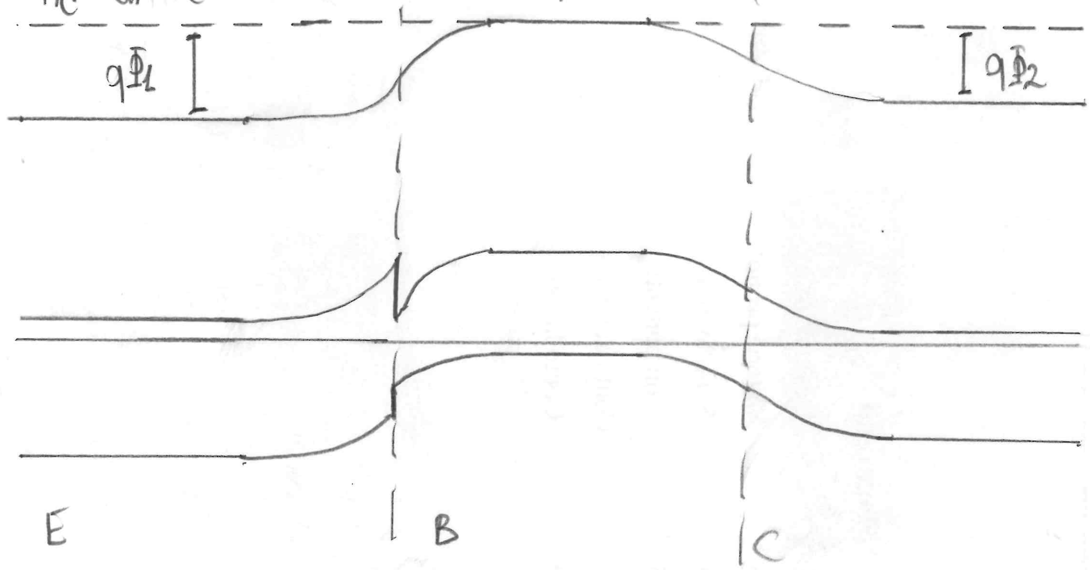
c) $\mathcal{E}(\phi^-) = 79{,}06$ KV/cm (conto 74 e rotti in ϕ^+!)

d) $n_p'(x_p) = 3{,}416$ E 13;

$p_n'(x_p) = 0{,}44$ E 10.

04/02/08

a) La struttura ha un d. a bande del tipo:



$\Delta E_g = 0{,}36$ eV;
$\Delta E_C = 0{,}224$ eV;
$\Delta E_V = 0{,}136$ eV.

$$q\Phi_1 = q\Phi_B - q\Phi_E = \left[q\chi_B + E_{gB} - (E_F - E_V)\right] - \left[q\chi_E + (E_C - E_F)\right]$$
$$= q\Delta\chi + E_{gB} + k_BT\ln\left(\frac{N_{AB}\,N_{DE}}{N_{VB}\,N_{CE}}\right) = 1{,}716 \text{ eV}.$$

$$q\Phi_2 = q\Phi_C - q\Phi_B = \left[\cancel{q\chi_C} + (E_C - E_F)\right] - \left[\cancel{q\chi_B} + E_{gB} - (E_F - E_V)\right] =$$
$$= -E_{gB} + k_BT\ln\left(\frac{N_{VB}N_{CC}}{N_{AB}N_{DC}}\right) = -1{,}323 \text{ eV}.$$

b) Ricordo la definizione di γ_F:

$$\gamma_F = \frac{J_{nB}(x_{BE})}{J_{nB}(x_{BE}) + J_{pE}(x_{EB})}$$

Calcolo $p'_{nE}(x)$: considero ipotesi lato "corto"!

$$\hookrightarrow \phi = -\frac{1}{q}\frac{\partial J_p}{\partial x} - \frac{p_n'}{\tau_p}; \longrightarrow J_p = -\frac{\partial p_n'}{\partial x} D_n \longrightarrow \frac{\partial^2 p_n'(x)}{\partial^2} = \frac{p_n'(x)}{L_p^2};$$

$$\hookrightarrow p_n'(x) = A\exp\left(\frac{x}{L_p}\right) + B\exp\left(-\frac{x}{L_p}\right); \quad p_n'(W_E) = \phi = A\exp\left(\frac{W_E}{L_p}\right) + B\exp\left(-\frac{W_E}{L_p}\right)$$

$$\hookrightarrow B = -A\exp\left(\frac{2W_E}{L_p}\right);$$

$$p_n'(x_{EB}) = A\exp\left(\frac{x_{EB}}{L_p}\right) - A\exp\left(-\frac{x_{EB}}{L_p}\right)\exp\left(\frac{2W_E}{L_p}\right)$$

$$\longrightarrow A\left[\exp\left(\frac{x_{EB}}{L_p}\right) - \exp\left(-\frac{x_{EB} - 2W_E}{L_p}\right)\right] = p_n'(x_{EB}) \longrightarrow A = \frac{p_n'(x_{EB})\exp\left(-\frac{W_E}{L_p}\right)}{2\sinh\left(\frac{x_{EB} - W_E}{L_p}\right)};$$

$$B = -\frac{p_n'(x_{EB})\exp\left(\frac{W_E}{L_p}\right)}{2\sinh\left(\frac{x_{EB}-W_E}{L_p}\right)}.$$

$$\rightarrow p_n'(x) = \frac{1}{2\sinh\left(\frac{x_{EB}-W_E}{L_p}\right)}\left[p_n'(x_{EB})\exp\left(\frac{x-W_E}{L_p}\right) - p_n'(x_{EB})\exp\left(\frac{W_E-x}{L_p}\right)\right] =$$

$$= \frac{\cancel{2}\sinh\left(\frac{x-W_E}{L_p}\right)}{\cancel{2}\sinh\left(\frac{x_{EB}-W_E}{L_p}\right)} p_n'(x_{EB}) \xrightarrow[\approx \phi]{\text{Taylor}} \boxed{\frac{x-W_E}{x_{EB}-W_E} p_n'(x_{EB})}$$

$$J_p(x_{EB}) = \left.\frac{\partial p_n'(x)}{\partial x}\right|_{x_{EB}} = qD_{nE}\frac{p_n'(x_{EB})}{W_E'} =$$

Considerando $x_{BE} = \phi$, dovrei avere:

$$n_p'(x) = n_p'(\phi)\frac{\sinh\left(\frac{W_B - x}{L_n}\right)}{\sinh\left(\frac{W_B}{L_n}\right)} + n_p'(W_B)\frac{\sinh\left(\frac{x}{L_n}\right)}{\sinh\left(\frac{W_B}{L_n}\right)}$$

Derivo e valuto in $x = \phi$:

$$\rightarrow \frac{\partial n_p'(x)}{\partial x} = -\frac{n_p'(\phi)}{L_n}\left.\frac{\cosh\left(\frac{W_B - x}{L_n}\right)}{\sinh\left(\frac{W_B}{L_n}\right)}\right|_\phi + \frac{n_p'(W_B)}{L_n}\left.\frac{\cancel{\cosh\left(\frac{x}{L_n}\right)}}{\sinh\left(\frac{W_B}{L_n}\right)}\right|_\phi =$$

$$= -\frac{n_p'(\phi)}{L_n}\coth\left(\frac{W_B}{L_n}\right) + \frac{n_p'(W_B)}{L_n}\cdot\left[\sinh\left(\frac{W_B}{L_n}\right)\right]^{-1}.$$

$$\approx -\frac{n_p'(\phi)}{W_B} + \frac{n_p'(W_B)}{W_B}. \rightarrow J_n(\phi) = qD_n\left.\frac{\partial n_p}{\partial x}\right|_\phi \underset{\substack{\uparrow \\ \text{approx.} \\ \text{RAD}}}{\approx} \frac{qD_n}{W_B}\left[n_p(\phi) - \cancel{n_p'(W_B)}\right]$$

$$n_p'(\phi) = \frac{N_{CB}}{N_{CE}} N_{DE}\exp\left(-\frac{q\Phi_i + \Delta E_C}{k_BT}\right)\left[\exp\left(\frac{V_{BE}}{V_T}\right) - 1\right];$$

$$p_n'(x_n) = \frac{N_{VE}}{N_{VB}} N_{AB}\exp\left(-\frac{q\Phi_i + \Delta E_V}{k_BT}\right)\left[\exp\left(\frac{V_{BE}}{V_T}\right) - 1\right].$$

$$\longrightarrow \gamma_F = \left[1 + \frac{J_{pE}(x_{EB})}{J_{nB}(\underbrace{x_{BE}}_{=\phi})}\right]^{-1} = \left[1 + \frac{N_{VE}N_{AB}D_{pE}W_B N_{CE}\exp\left(-\frac{\Delta E_C}{k_BT}\right)}{N_{VB}N_{CB}N_{DE}W_E D_{nB}\exp\left(-\frac{\Delta E_V}{k_BT}\right)}\right]^{-1}$$

c) A destra ho una giunzione p-n:

$\varepsilon_s = 13,1$; $X_p = x_d \frac{N_{DC}}{N_{DC}+N_{AB}} = \frac{N_{DC}}{N_{DC}+N_{AB}} \sqrt{\frac{2\varepsilon_s}{q}\left[\frac{1}{N_{AB}}+\frac{1}{N_{DC}}\right](V_{bi}-V_a)} =$

$= 21 \text{ nm}$;

Per l'altra, discorso simile, ma con cambio di ε:

$$\frac{q N_{DE}}{2\varepsilon_E} x_{np}^2 + \frac{q N_{AB}}{2\varepsilon_B} x_{pd}^2 = \Phi_1 \longrightarrow x_{nd} = \frac{N_{AB}}{N_{DE}} x_{pd}$$

$$\hookrightarrow \frac{q \cancel{N_{DE}}}{2\varepsilon_E} \frac{N_{AB}^2}{N_{DE}^{\cancel{2}}} x_{pd}^2 + \frac{q N_{AB}}{2\varepsilon_B} x_{pd}^2 = \Phi_1 ;$$

$$\hookrightarrow \frac{q N_{AB}}{2}\left[\frac{N_{AB}}{\varepsilon_E N_{DE}} + \frac{1}{\varepsilon_B}\right] x_{pd}^2 = \Phi_1$$

$$\longrightarrow x_{pd} = \sqrt{\frac{2}{q N_{AB}} \frac{\varepsilon_B \varepsilon_E N_{DE}}{\varepsilon_E N_{DE} + \varepsilon_B N_{AB}} (\Phi_{bi} - V_a)}$$

$\longrightarrow x_p = 8,3 \text{ nm}$;

$\Longrightarrow W_B' = W_B - x_p - x_n = 370,1 \text{ nm}$

d) Con un BJT dalla geometria / drogaggi analoghi, avrei, come regioni di svuotamento: (in GaAs)

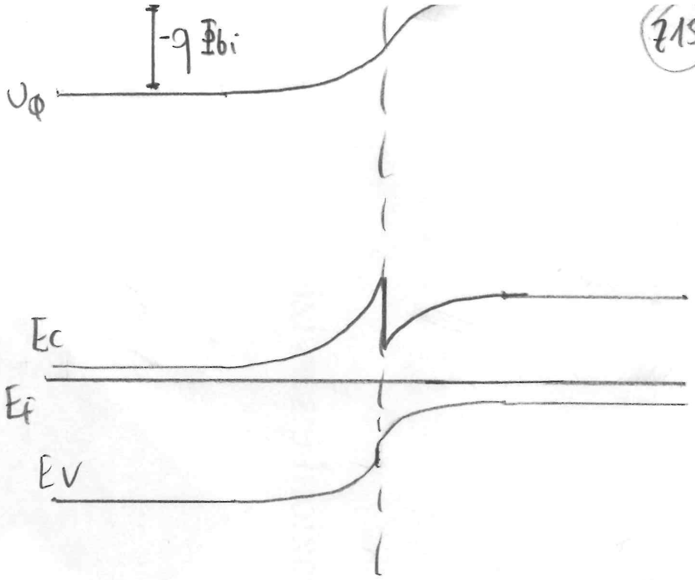
$x_p|_{sx} = 5,6 \text{ nm} \longrightarrow$ l'unica cosa che cambia è la Φ_{bi} (che ho approssimato $\Phi_1' = \Phi_2$).

$x_p|_{dx}$ medesimo

Cambia poco. Per migliorare, si dovrebbero cambiare i drogaggi !!!

04/02/2010

Esercizio 2



a) $\Delta E_g = E_{g2} - E_{g1} = -0{,}34\ eV$;

$\Delta E_c = 0{,}204\ eV$;

$\Delta E_v = 0{,}136\ eV$.

$$q\Phi_{bi} = q\Phi_2 - q\Phi_1 =$$

$$= \left[q\chi_2 + E_{g2} - (E_F - E_V)\right] - \left[q\chi_1 + (E_C - E_F)\right] =$$

$$= q\Delta\chi + E_g + k_B T \ln\left(\frac{N_{D1} N_{A2}}{N_{C1} N_{V2}}\right) = 1{,}68\ eV.$$

b) Di getto posso scrivere che:

$$\Phi_{bi} = \frac{qN_D}{2\varepsilon_1} x_{n\phi}^2 + \frac{qN_A}{2\varepsilon_2} x_{p\phi}^2 \quad \left[\begin{array}{l}\text{l'elettrostatica è identica alla p-n,} \\ \text{cambia solo } \varepsilon\end{array}\right].$$

$$\hookrightarrow x_{p\phi} = x_{n\phi}\frac{N_D}{N_A} \longrightarrow \Phi_{bi} = \frac{qN_D}{2\varepsilon_1} x_{n\phi}^2 + \frac{q\cancel{N_A}}{2\varepsilon_2}\frac{N_D^2}{N_A^{\cancel{2}}} x_{n\phi}^2 =$$

$$= \frac{qN_D}{2} x_{n\phi}^2 \left[\frac{1}{\varepsilon_1} + \frac{N_D}{\varepsilon_2 N_A}\right] = \Phi_{bi} \longrightarrow x_{n\phi} = \sqrt{\frac{2}{qN_D}\frac{\varepsilon_1 \varepsilon_2 N_A}{\varepsilon_1 N_D + \varepsilon_2 N_A}\Phi_{bi}}$$

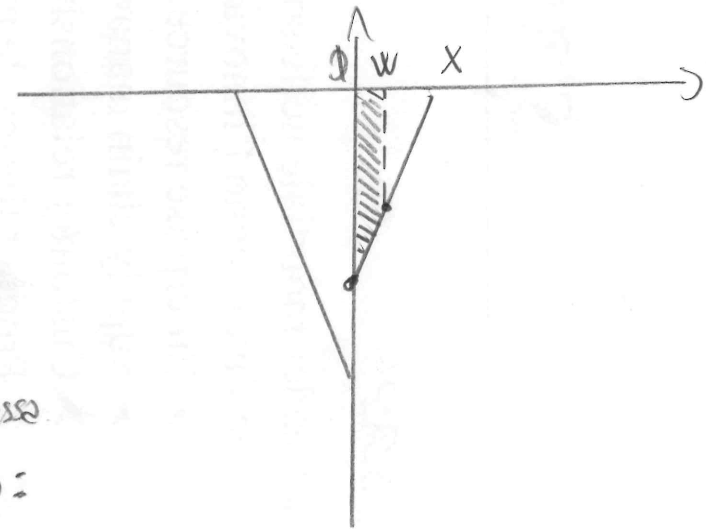
$$= 48{,}8\ nm;$$

$$x_{p\phi} = x_{n\phi}\frac{N_D}{N_A} = 193{,}2\ nm.$$

c) L'obiettivo è: calcolare la w.

Un modo è partire dal campo $\mathcal{E}$ nel semiconduttore p:

$$\mathcal{E}(x) = \int -\frac{qN_A}{\varepsilon_2}\,dx = -\frac{qN_A}{\varepsilon_2}\left[x - x_{p\phi}\right];$$



L'area tratteggiata è la $\Delta\Phi$ che ci interessa.

Come si può fare? Beh: area del trapezio:

$$\Delta\Phi = \frac{1}{2}\left[\mathcal{E}(w) + \mathcal{E}(\phi)\right]\cdot w$$ dove tutto è noto tranne w!

So che:

$$\mathcal{E}(\phi) = \frac{qN_A}{\varepsilon_2} x_{p\phi} \; ; \quad \mathcal{E}(W) = -\frac{qN_A}{\varepsilon_2}\left[W - x_{p\phi}\right] = \frac{qN_A}{\varepsilon_2}\left[x_{p\phi} - W\right];$$

$$\hookrightarrow \Delta\Phi = W \cdot \frac{1}{2}\left[2\frac{qN_A}{\varepsilon_2} x_{p\phi} - \frac{qN_A}{\varepsilon_2} W\right] = \frac{qN_A}{\varepsilon_2}\left[2x_{p\phi} - W\right]\frac{W}{2}$$

$$\longrightarrow \frac{W}{2}\left[2x_{p\phi} - W\right] = \frac{\varepsilon_2}{qN_A}\Delta\Phi \; ;$$

$$W^2 - 2x_{p\phi} W + \frac{2\varepsilon_2}{qN_A}\Delta\Phi = \phi$$

$$\hookrightarrow \quad W = x_{p\phi} - \sqrt{x_{p\phi}^2 - \frac{2\varepsilon_2}{qN_A}\Delta\Phi}\,.$$

d) Considera al posto di $x_{p\phi}$, la $x_p(V_a)$:

$$\hookrightarrow (W - x_p) = -\sqrt{\cdots} \xrightarrow{()^2} W^2 - 2Wx_p + \cancel{x_p^2} = \cancel{x_p^2} - \frac{2\varepsilon_2}{qN_A}\Delta\Phi$$

$$\hookrightarrow x_p = \frac{W}{2} + \frac{\varepsilon_2}{qN_A W}\Delta\Phi.$$

Ma:

$$x_p = \sqrt{\frac{2\varepsilon N_{eq}}{qN_{A2}^2}(\Phi_i - V_a)} \longrightarrow \Phi_i - V_a = x_p^2 \cdot \frac{qN_{A2}^2}{2\varepsilon N_{eq}}$$

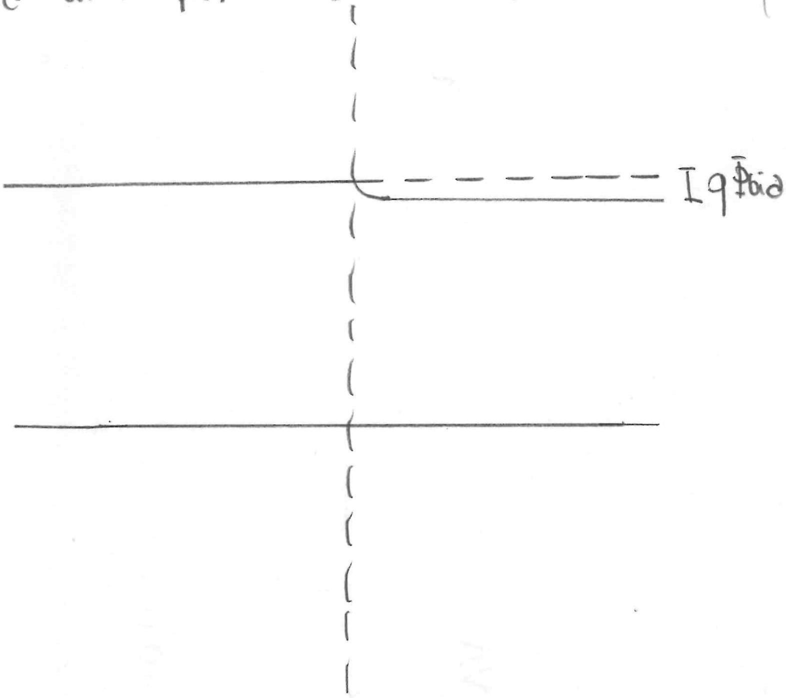
$$\hookrightarrow V_a = \Phi_i - \frac{qN_{A2}^2}{2\varepsilon N_{eq}} x_p^2 = \Phi_i - \frac{qN_{A2}^2}{2\varepsilon N_{eq}}\left[\frac{W}{2} + \frac{\varepsilon_2}{qN_A W}\Delta\Phi\right]^2.$$

e) Ciò si può girare, con $V_a = \phi$, esplicitando $N_{eq}\varepsilon$ e portando tutti gli N_{A2} da una parte. Purtroppo però, $\Phi_i \propto \ln(N_{A2})$, dunque l'espressione non è risolubile se non con metodi numerici.

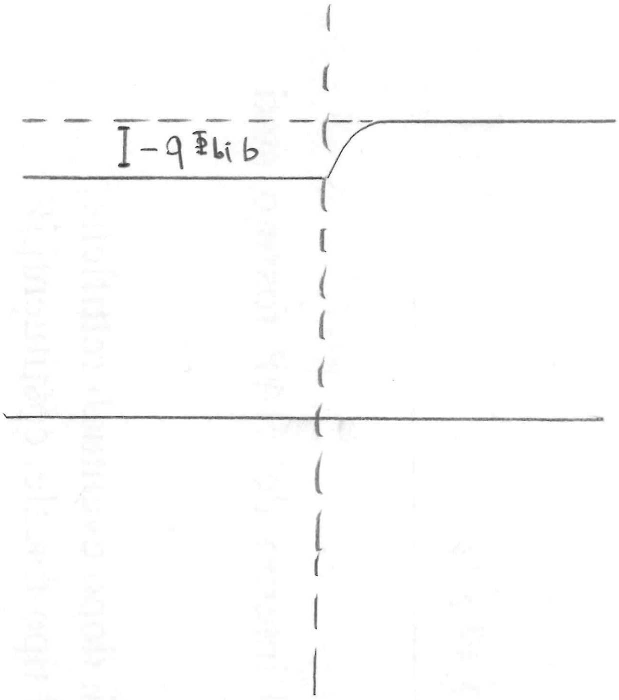
Esercizio 2

Da una parte ho Al ($q\Phi_M = 4,1$ eV); dall'altra, altro.

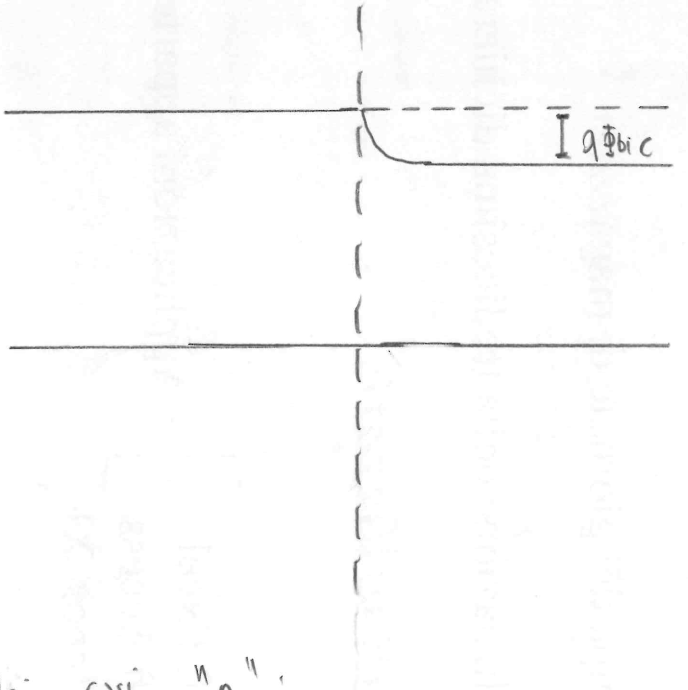
a



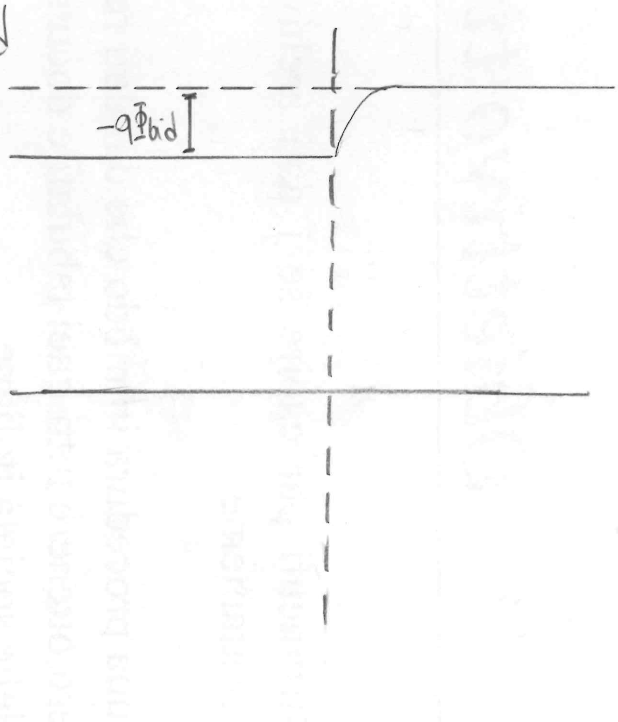
b



c



d



Nei casi "n":

$$q\Phi_{bi} = q\Phi_M - q\Phi_{S_n} = q\Phi_M - \left[q\chi_S + (E_C - E_F)\right] = q\Phi_M - q\chi_S + k_BT\ln\left(\frac{N_D}{N_C}\right);$$

Nei casi "p":

$$q\Phi_{bi} = q\Phi_M - q\Phi_{S_p} = q\Phi_M - \left[q\chi_S + E_g - (E_F - E_V)\right] = q\Phi_M - q\chi_S - E_g + k_BT\ln\left(\frac{N_A}{N_V}\right)$$

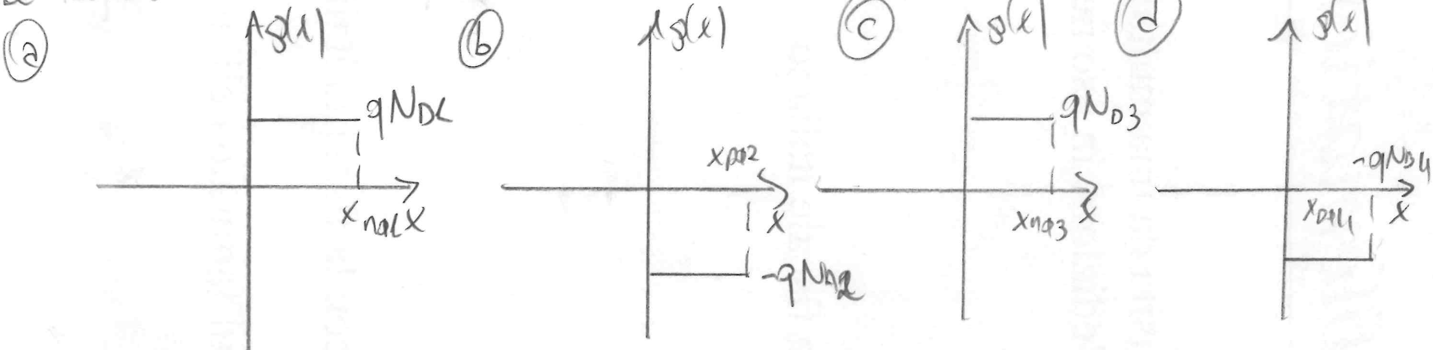
Calcolo dunque le quattro barriere:

$q\Phi_{bia} = 0{,}07517$ eV; $q\Phi_{bib} = -1{,}499$ eV; $q\Phi_{bic} = 0{,}382$ eV; $q\Phi_{bid} = -1{,}454$ eV

I disegni sono fatti dopo questi calcoli.

Tutte e quattro le strutture presentano, come si evince dai diagrammi a bande, una regione di svuotamento nel semiconduttore. Ciò per la teoria di Schottky coincide con l'avere raddrizzamento.

Le densità di carica saranno:



x_i si calcola, da formulario:

$$x_d = \sqrt{\frac{2\varepsilon}{qN_D}(V_{bi} - V)}$$

$\rightarrow$ $x_{d1} = 45{,}82$ nm; $x_{d2} = 204{,}6$ nm; $x_{d3} = 99{,}76$ nm; $x_{d4} = 191{,}6$ nm.

Essendo tutte raddrizzanti, calcolo tutte le correnti:

$$\begin{cases} q\Phi_{B1,2} = \overset{(a)}{0{,}136} \rightarrow \overset{(b)}{1{,}354}; \\ q\Phi_{B3,4} = \overset{(c)}{0{,}454} \rightarrow \overset{(d)}{1{,}306} \end{cases}$$

$J_1 = 57{,}77$ kA/cm^2 [enorme]

$J_2 = 261$ aA/cm^2

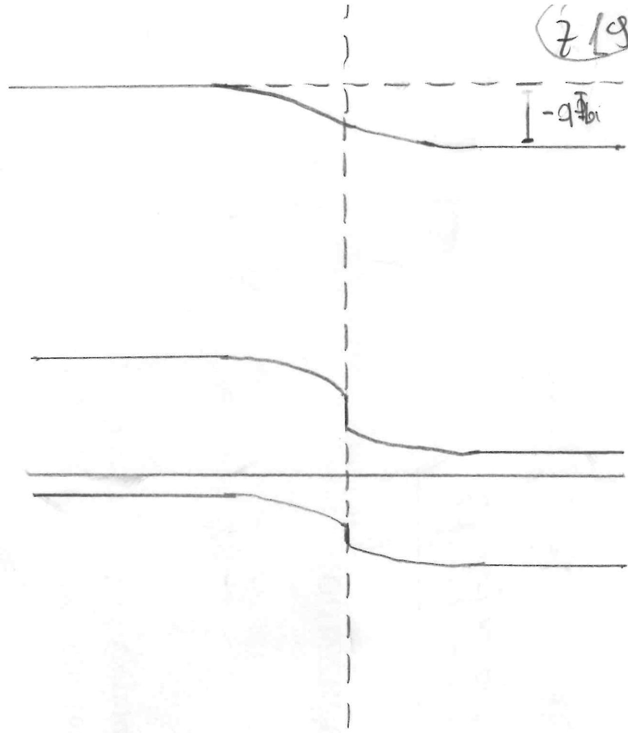
$J_3 = 281{,}8$ mA/cm^2

$J_4 = 1{,}634$ fA/cm^2

Nota: per a e b, si ha un Φ_B, e per c e d un'altra, poiché essa dipende **solo** dai materiali. Per b e d, dovrò usare la "barriera complementare a E_g".

$[q\Phi_B] = eV$.

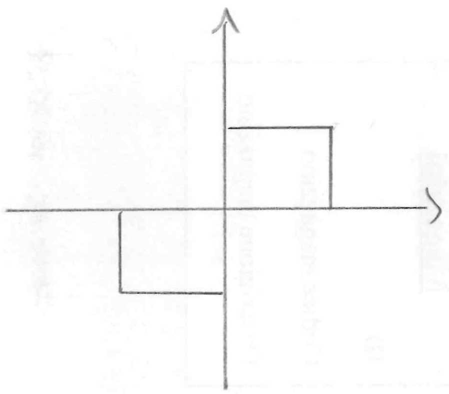
Tema di esame 01/09/98



a)
$$q\Phi_{bi} = q\Phi_2 - q\Phi_1 = \left[q\chi_2 + (E_C - E_F)\right] -$$
$$+ \left[q\chi_1 + E_{g1} - (E_F - E_V)\right] =$$
$$= q\Delta\chi - E_{g1} + k_B T \ln\left(\frac{N_{C2}\, N_{V1}}{N_{D2}\, N_{A1}}\right) =$$
$$= -1{,}231 \text{ eV}.$$

$\Delta E_C = -q\Delta\chi = -0{,}32$ eV ;
$\Delta E_V = -\Delta E_g - q\Delta\chi = -30$ meV.

A questo punto, per le regioni svuotate, derivo tutta la pantomima:

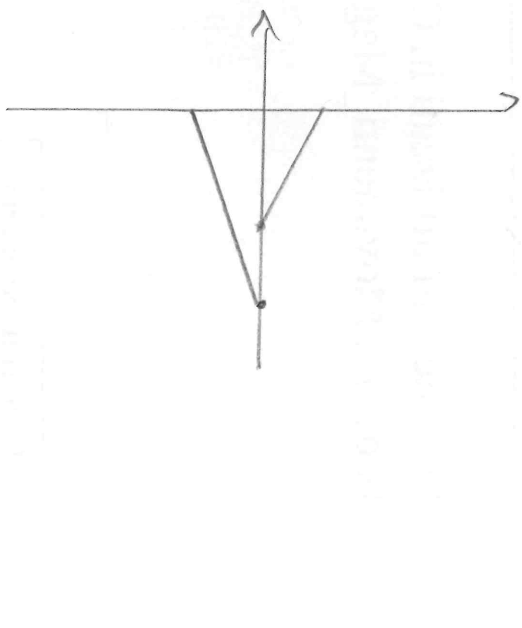


Nota: in questo ambito, ho $N_{A1} = N_{D2}$.
Ciò ci aiuta poiché:
$\cancel{q}\cancel{N_{A1}}\, x_{p\phi} = \cancel{q}\cancel{N_{D2}}\, x_{n\phi} \rightarrow x_{p\phi} = x_{n\phi}$!

$$\Phi_{bi} = \frac{qN_{D2}}{2\varepsilon_2} x_{n\phi}^2 + \frac{qN_{A1}}{2\varepsilon_1} x_{p\phi}^2 =$$
$$= \frac{qN_{D2}}{2} x_{n\phi}^2 \left[\frac{1}{\varepsilon_2} + \frac{1}{\varepsilon_1}\right]$$

$$x_{n\phi} = \sqrt{\frac{2}{qN_{D2}}\ \varepsilon_1 \oplus \varepsilon_2}\ .$$

b) $\varepsilon_{r1} < \varepsilon_{r2}$: il campo massimo sarà nel "1" $\longrightarrow$



$$\mathcal{E}_{max} = \mathcal{E}(\phi^-) = \frac{-qN_A}{\varepsilon_1} x_{p\phi}$$

c) Ne ricavo una, e l'altra per dualità. So che:

$$n_p(x_p)\,p_n(x_n) = N_{C1}\exp\left(-\frac{E_C(x_p)-E_F}{k_BT}\right)N_{V2}\exp\left(-\frac{E_F-E_V(x_n)}{k_BT}\right) =$$

$$= N_{C1}\,N_{V2}\,\exp\left(\frac{E_V(x_n)-E_C(x_p)}{k_BT}\right);$$

So, dal d. a bande, che:

$$-\left[E_V(x_n)-E_C(x_p)\right] = q\Phi_{bi}+\Delta E_C+E_{g2} = q\Phi_{bi}+\Delta E_V+E_{g1}.$$

Considero $p_n(x_n)$:

$$n_n(x_n)\,p_n(x_n) \approx N_{D2}\,p_n(x_n) = N_{C2}\,N_{V2}\,\exp\left(-\frac{E_{g2}}{k_BT}\right)$$

$$\hookrightarrow p_n(x_n) \approx \frac{N_{C2}N_{V2}}{N_{D2}}\exp\left(-\frac{E_{g2}}{k_BT}\right);$$

$$\hookrightarrow n_p(x_p)\,p_n(x_n) \Rightarrow n_p(x_p) = \frac{N_{D2}}{N_{C2}\cancel{N_{V2}}}N_{C1}\cancel{N_{V2}}\cancel{\exp\left(\frac{E_{g2}}{k_BT}\right)}\exp\left(-\frac{q\Phi_{bi}+\Delta E_C+\cancel{E_{g2}}}{k_BT}\right).$$

$$\hookrightarrow n_p'(x_p) = \frac{N_{C1}}{N_{C2}}N_{D2}\exp\left(-\frac{q\Phi_{bi}+\Delta E_C}{k_BT}\right)\left[\exp\left(\frac{V_A}{V_T}\right)-1\right].$$

per dualità:

$$p_n'(x_n) = \frac{N_{V2}}{N_{V1}}N_{A1}\exp\left(-\frac{q\Phi_{bi}+\Delta E_V}{k_BT}\right)\left[\exp\left(\frac{V_A}{V_T}\right)-1\right].$$

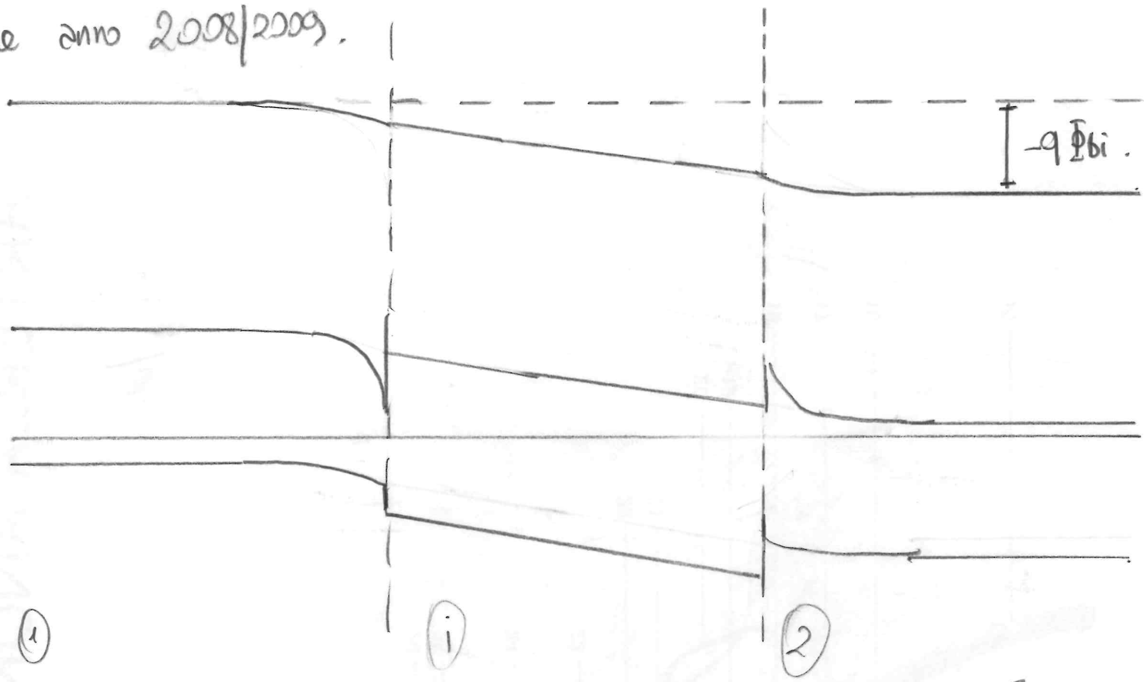
Dunque:

$$\frac{p_n'(x_n)}{n_p'(x_p)} = \frac{N_{V2}N_{C2}N_{A1}}{N_{V1}N_{C1}N_{D2}}\exp\left(-\frac{\Delta E_V-\Delta E_C}{k_BT}\right)$$

Simulazione anno 2008/2009.

Esercizio

a)



$$q\Phi_{bi} = q\Phi_2 - q\Phi_1 = \left[q\chi_2 + |E_C - E_F|\right] - \left[q\chi_1 + E_{g1} - (E_F - E_V)\right] =$$

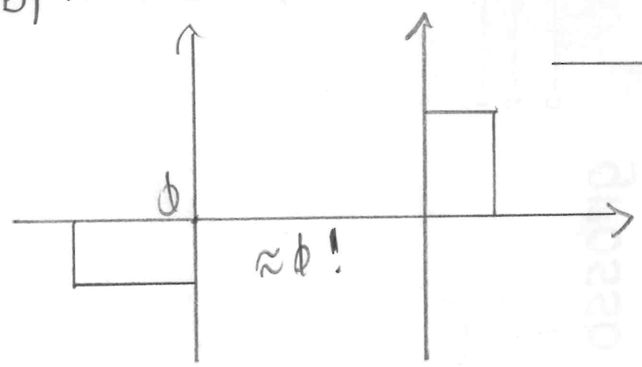
$$= -E_{g1} + k_BT\ln\left(\frac{N_{C2}N_{V1}}{N_{A1}N_{D2}}\right) = -1{,}218\ eV.$$

$\Delta E_g = 0{,}34$ eV

$\Delta E_C = 0{,}204$ eV;

$\Delta E_V = 0{,}136$ eV.

b) Si consideri la seguente ρ:



$\longrightarrow \Phi_1$:

$$\int -\frac{qN_A}{\varepsilon_1}dx = -\frac{qN_A}{\varepsilon_1}\left[x - x_{p0}\right];$$

$$\int \frac{qN_D}{\varepsilon_1}dx = \frac{qN_D}{\varepsilon_1}\left[x - x_{n0}\right];$$

$$\mathcal{E}(0^-) = \mathcal{E}(0^+)\frac{\varepsilon_2}{\varepsilon_1} \rightarrow \mathcal{E}(0^+) = \mathcal{E}(0^-)\frac{\varepsilon_1}{\varepsilon_2} = \frac{qN_A}{\varepsilon_1}x_{p0} \quad (x_{p0} < 0!)$$

$$\rightarrow \mathcal{E}(0^+) = \frac{qN_A}{\varepsilon_2}x_{p0}.$$

$$\Phi_{bi} = \underbrace{(\overset{-}{+})\frac{qN_A}{\varepsilon_2}x_{p0}W_i}_{i}\ \underbrace{(\overset{-}{+})\frac{qN_A}{2\varepsilon_1}x_{p0}^2}_{p} - \underbrace{\frac{qN_D}{2\varepsilon_1}x_{n0}^2}_{n} \qquad \text{ma!}\ \ x_{n0} = -x_{p0}\frac{N_A}{N_D}$$

$$\rightarrow \frac{qN_A}{\varepsilon_2} x_{p\phi} w_i + \frac{qN_A}{2\varepsilon_1} x_{p\phi}^2 + \frac{qN_A^2}{2\varepsilon_1 N_D} x_{p\phi}^2 = \Phi_{bi}$$

$$\rightarrow x_{p\phi}^2 \left[\frac{qN_A}{2\varepsilon_1} + \frac{qN_A^2}{2\varepsilon_1 N_D} \right] + \frac{qN_D}{\varepsilon_2} w_i x_{p\phi} - \Phi_{bi} = \phi$$

$$\rightarrow x_{p\phi}^2 \left[\frac{qN_A N_D + qN_A^2}{2\varepsilon_1 N_D} \right] + \frac{qN_A}{\varepsilon_2} w_i x_{p\phi} - \Phi_{bi} = \phi$$

$$\rightarrow x_{p\phi}^2 + x_{p\phi}$$

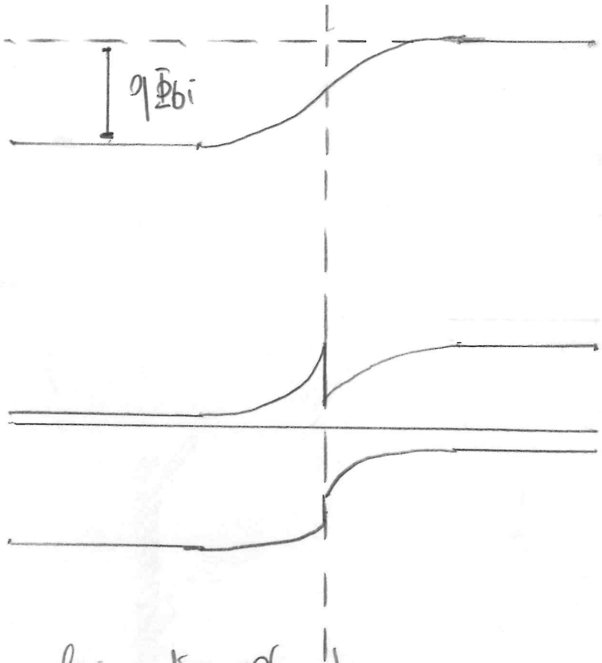
Tema di esame 04/02/10 - Esercizio

a)

$\Delta E_g = 0{,}34\ eV$;

$\Delta E_c = 0{,}204\ eV$;

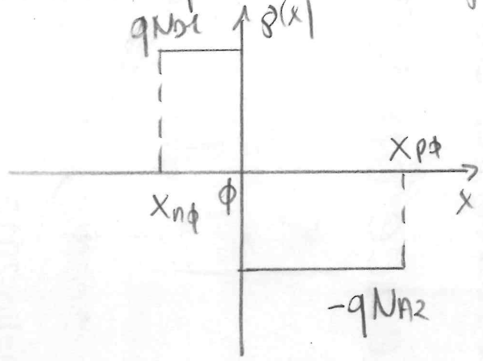
$\Delta E_v = 0{,}136\ eV$.



$$q\Phi_{bi} = q\Phi_2 - q\Phi_1 = \left[q\chi_2 + E_{g2} - (E_F - E_V)\right] - + \left[q\chi_1 + (E_C - E_F)\right] =$$

$$= q\Delta\chi + E_{g2} + k_B T \ln\left(\frac{N_{D1} N_{A2}}{N_{C1} N_{V2}}\right) = 1{,}68\ eV$$

b) Calcolo il potenziale in ogni zona. Scelgo come riferimento $\varphi(+\infty)$.



per $x > x_{p\phi}$, $\varphi(x) = \phi$;

per $\phi < x < x_{p\phi}$, ho:

$$\mathcal{E}(x) = \int -\frac{qN_{A2}}{\varepsilon_2}\,dx = -\frac{qN_{A2}}{\varepsilon_2}\left[x - x_{p\phi}\right].$$

$$\varphi(x) = \frac{qN_{A2}}{2\varepsilon_2}\left[x - x_{p\phi}\right]^2 \longrightarrow \varphi(\phi^+) = \frac{qN_A}{2\varepsilon_2} x_{p\phi}^2.$$

Per $x_{n\phi} < x < \phi$, ho:

$$\mathcal{E}(x) = \int \frac{qN_{D1}}{\varepsilon_1}\,dx = \frac{qN_{D1}}{\varepsilon_1}\left[x - x_{n\phi}\right]; \longrightarrow \varphi(x) = -\frac{qN_{D1}}{2\varepsilon_1}\left[x - x_{n\phi}\right]^2 + c;$$

c può esser stabilita imponendo la continuità del potenziale;

$$\varphi(\phi^-) = \varphi(\phi^+) \Longrightarrow -\frac{qN_{D1}}{2\varepsilon_1} x_{n\phi}^2 + c = \frac{qN_{A2}}{2\varepsilon_2} x_{p\phi}^2$$

$$\hookrightarrow \varphi(x) = -\frac{qN_{D1}}{2\varepsilon_1}\left[x - x_{n\phi}\right]^2 + \frac{qN_{A2}}{2\varepsilon_2} x_{p\phi}^2 + \frac{qN_{D1}}{2\varepsilon_1} x_{n\phi}^2.$$

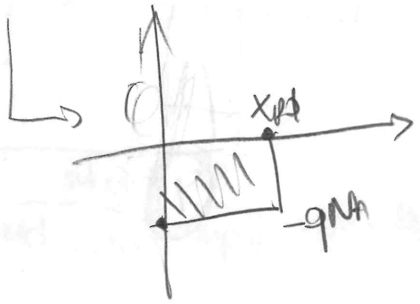
Per $x < x_{n\phi}$, $\varphi(x) = \Phi_{bi} = \frac{qN_{A2}}{2\varepsilon_2} x_{p\phi}^2 + \frac{qN_{D1}}{2\varepsilon_1} x_{n\phi}^2$.

Uso questa e la neutralità globale: $x_{p\phi} = x_{n\phi}\frac{N_{D1}}{N_{A2}}$

$$\hookrightarrow \Phi_{bi} = \frac{qN_{A2}}{2\varepsilon_2}\frac{N_{D1}^2}{N_{A2}^2} x_{n\phi}^2 + \frac{qN_{D1}}{2\varepsilon_1} x_{n\phi}^2 \longrightarrow x_{n\phi}^2 \frac{qN_{D1}}{2}\left[\frac{N_{D1}}{\varepsilon_2 N_{A2}} + \frac{1}{\varepsilon_1}\right]$$

$$\longrightarrow x_{n\phi} = \sqrt{\frac{2}{qN_{D1}}\frac{\varepsilon_1\varepsilon_2 N_{A2}}{\varepsilon_1 N_{D1} + \varepsilon_2 N_{D2}}} = \sqrt{\frac{2}{qN_{D1}^2}\frac{\varepsilon_1\varepsilon_2 N_{D1} N_{A2}}{\varepsilon_1 N_{D1} + \varepsilon_2 N_{D2}}}$$

Provo a calcolare il potenziale per bene!



$$\to \quad \mathcal{E}(x) = \int \frac{-qN_A}{\varepsilon_2}\,dx = -\frac{qN_A}{\varepsilon_2}\left[x - x_{pp}\right];$$

$$\varphi(x) = -\int \frac{q}{\ldots} = \boxed{\frac{qN_A}{2\varepsilon_2}\left[x - x_{pp}\right]^2}$$

$$\boxed{-q\,\varphi(x) = -\frac{q^2 N_A}{2\varepsilon_2}\left[x - x_{pp}\right]^2}$$

$$E_C(\phi^-) - E_C(\phi^+) = -\Delta E_C = \boxed{q\Delta x};$$

$$E_C(\phi^+) = E_C(\phi^-) - \underset{\text{noto}}{\Delta E_C}; \quad E_C(\phi^+) = -q\,\varphi(\phi^-)$$

$$\to \varphi(\phi^-) = \frac{qN_D}{2\varepsilon_1} x_{np}^2;$$

$$\to \boxed{E_C(\phi^+) = -\frac{q^2 N_D}{2\varepsilon_1} x_{np}^2 - \Delta E_C}$$

$$E_C(\phi^-) - E_C(\phi^+) = q\Delta E_C;$$

$E_C(+\infty)$ rif;

$$q\,\varphi(x) = E_C(w) - E_C(+\infty) = (E_C(\phi^+) - E_C(\infty))$$

$$q\Delta E_C = E_C(\phi^-) - E_C(\phi^+) = E_C(\phi^-) + E_C(+\infty) - E_C(+\infty) - E_C(\phi^+)$$

$$\hookrightarrow q\Delta E = q\,\varphi(\phi^-) - q\,\varphi(\phi^+) = q\,\varphi(\phi^-) - q\,\varphi(w)$$

$$\hookrightarrow \varphi(w) - \varphi(\phi^-) + \Delta E = \phi.$$

MA:

$$\varphi(x) = \frac{qN_A}{2\varepsilon}x^2 - \frac{qN_A x_d}{\varepsilon}x + K$$

$$\hookrightarrow \frac{qN_A}{2\varepsilon}w^2 - \frac{qN_A x_d}{\varepsilon}w + \Delta E = \phi \to w = x_d - \sqrt{x_d^2 - \frac{2\varepsilon}{qN_A}\Delta E}$$

Trucco: riconduci al problema NOTO! conosco $\boxed{\varphi(x)}$! e so che $\boxed{E = -q\varphi}$

<Discorsetto> 2

$\hookrightarrow N(E) = \gamma_P \sqrt{E_V - E}$; $f(E) = \left[1 + \exp\left(\frac{E-E_F}{k_BT}\right)\right]^{-1}$;

$$f_C(E) = 1 - f(E) = \frac{\cancel{1} - \cancel{1} + \exp\left(\frac{E-E_F}{k_BT}\right)}{1 + \exp\left(\frac{E-E_F}{k_BT}\right)} = \frac{1}{1+\exp\left(\frac{E_F-E}{k_BT}\right)} .$$

$$\longrightarrow P = \int_{-\infty}^{E_V} \frac{\gamma_P \sqrt{E_V - E}}{1+\exp\left(\frac{E_F-E}{k_BT}\right)} dE \simeq \int \gamma_P \exp \sqrt{E_V - E} \exp\left(\frac{E-E_F}{k_BT}\right) dE =$$

$$= \gamma_P \exp\left(\frac{-E_F}{k_BT}\right) \int \sqrt{E_V - E} \exp\left(\frac{E}{k_BT}\right) .$$

Questo si scopre essere:

$$\hookrightarrow = N_V \exp\left(\frac{E_V - E_F}{k_BT}\right) .$$

$$n_i = N_C \exp\left(-\frac{E_C - E_{Fi}}{k_BT}\right) \longrightarrow n \approx n_i \exp\left(\frac{E_F - E_{Fi}}{k_BT}\right)$$

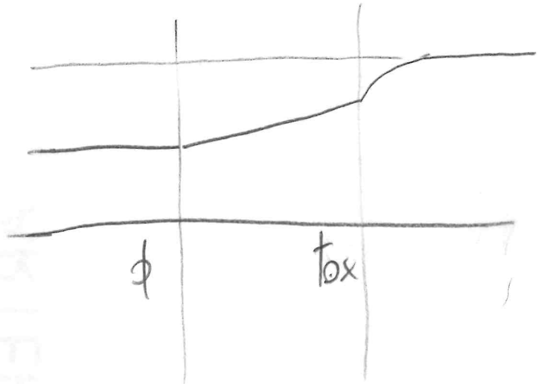
$$N_D = N_C \exp\left(-\frac{E_C - E_F}{k_BT}\right) ; \quad \frac{n_i^2}{N_D} = N_V \exp\left(-\frac{E_F - E_V}{k_BT}\right) ;$$

$\hookrightarrow$ ~~$np = n_i$~~ $\quad n = N_D$; $\quad p = \frac{n_i^2}{N_D}$;

$$\hookrightarrow \frac{N_D}{\frac{n_i^2}{N_D}} = \frac{N_D^2}{n_i^2} = \frac{N_C}{N_V} \exp\left(\frac{E_F - E_C + E_F - E_V}{k_BT}\right)$$

$$\hookrightarrow N_D \approx n_i \exp\left(\frac{E_F - E_{Fi}}{k_BT}\right) ; \quad E_F - E_{Fi} = k_BT \ln\left(\frac{N_D}{n_i}\right) ;$$

$E_F = E_{Fi} + \ldots$



$E(-\infty) = -qV_G$;

$E(+\infty) = -qV_B$;

$E(t_{ox}) = -q\varphi_{ch} - q$

$E(-\infty) - E(t_{ox}) = -qV_G - (-q\varphi_{ch} - \phi_s) \Rightarrow V_G - 2\phi_p - \phi_{ch} = V_{ox}$;

$E(t_{ox}) - E(+\infty) = -q\phi_{ch} - q\phi_s - (-qV_B) \rightarrow \phi_{ch} + 2\phi_p - V_B$.

$\hookrightarrow Q_t = -Q_n - Q_d \Longrightarrow Q_n = -Q_t - Q_d =$

$= -C_{ox}V_{ox} \underbrace{+ qN_A x_p}_{\text{giunzione } (p\text{-}n)!} = -C_{ox}(V_G - 2\phi_p - \phi_{ch}) + \sqrt{2qN_A\varepsilon_s(\phi_{ch} + 2\phi_p - V_B)}$

$\hookrightarrow \phi_{ch} = \phi$; $Q_n = \phi \Longrightarrow V_G = 2\phi_p + \sqrt{2qN_A\varepsilon_s(2\phi_p - V_B)}$

$= V_{Th0} + \frac{\left[\sqrt{2qN_A\varepsilon_s(2\phi_p - V_B)} - \sqrt{2qN_A\varepsilon_s(2\phi_p)}\right]}{C_{ox}}$

$I_D = W\oint J_n(x,y) = \text{drift} = W\int q\mu_n n \frac{\partial\varphi(y)}{\partial y}dx = q\mu_n W N(y)\frac{\partial\varphi}{\partial y}$;

$I_D = \frac{q\mu_n W}{L}\int N(y)\,d\varphi_{ch} = \frac{\mu_n C_{ox} W}{L}\int (V_{GS} - \phi_{ch} - V_{th})\,d\phi_{ch} =$

$= \frac{\mu_n C_{ox} W}{L}\left[(V_{GS} - V_{th})V_{DS} - \frac{V_{DS}^2}{2}\right]$.

Alcune note per provar a capir meglio 'sto etero strutture;

$\Delta E_g \triangleq E_{g2} - E_{g1}$;

$\Delta \chi = \chi_2 - \chi_1$.

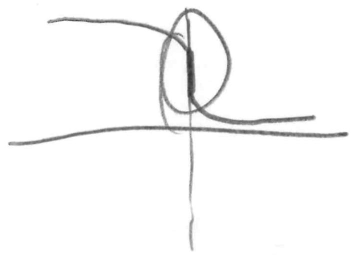
$\hookrightarrow \Delta E_C = E_{C2} - E_{C1} = \{[U_\phi - E_{C2}] - [U_\phi - E_{C1}]\} = \{-q\chi_2 - [-q\chi_1]\} =$

$= -q[\chi_2 - \chi_1] = \boxed{-q\Delta\chi}$

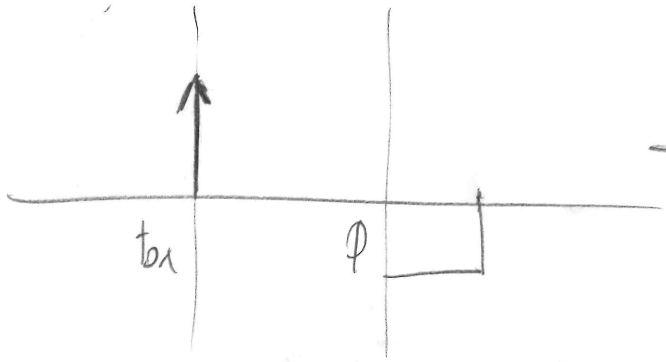
$\Delta E_V = -q\Delta\chi - \Delta E_g$.

Se $\chi_2 - \chi_1 > \phi$, allora $\boxed{\Delta E_C = E_{C2} - E_{C1} < \phi\ !}$

questo vuol dire che:

@ junction $E_{C2} < E_{C1} \Longrightarrow$ 

OK???



$\longrightarrow \mathcal{E}(x) = \int -\frac{qN_A}{\varepsilon_s}\, dx =$

$= -\frac{qN_A}{\varepsilon_s}\left[x - x_d\right];$

$\longrightarrow \varphi(x) = \frac{qN_A}{2\varepsilon_s}\left[x - x_d\right]^2;$

$\mathcal{E}(\phi^+) = \frac{qN_A}{\varepsilon_s} x_d; \quad \mathcal{E}(\phi^-) = \frac{qN_A}{\varepsilon_{ox}} x_d;$

$\varphi(x)\Big|_{ox} = -\frac{qN_A}{\varepsilon_{ox}} x_d x;$

$\longrightarrow \Phi_{bi} = \frac{qN_A}{2\varepsilon_s} x_d^2 + \frac{qN_A}{\varepsilon_{ox}} x_d t_{ox}$

$\longrightarrow x_d^2 + \frac{2\varepsilon_s}{\varepsilon_{ox}} x_d t_{ox} - \frac{2\varepsilon_s}{qN_A}\Phi_{bi} =$

$\longrightarrow x_d = -\frac{\varepsilon_s}{\varepsilon_{ox}} t_{ox} \pm \sqrt{\left(\frac{\varepsilon_s}{\varepsilon_{ox}} x_d\right)^2 + \frac{2\varepsilon_s}{qN_A}\Phi_{bi}}$

$\frac{d^2\varphi}{dx^2} = \frac{\rho(x)}{\varepsilon_s}; \quad \rho(x) = q\left(p - n - N_A^-\right); \quad n_{n\phi} = n_i \exp\left(\frac{-q\phi_p}{k_B T}\right);$

$p_{n\phi} = n_i \exp\left(\frac{q\phi_p}{k_B T}\right);$

$N_A^- = p_{n\phi} - n_{n\phi};$

$p = n_i \exp\left(-\frac{E_F - E_{Fi}}{kT}\right); \quad n = n_i \exp\left(\frac{E_F - E_{Fi}}{kT}\right); \quad p(x) = n_{n\phi} \exp\left(\frac{q\varphi(x) - q\phi_p}{k_B T}\right);$

$\rightarrow p(x) = n_{n\phi} \exp\left(-\frac{\varphi(x)}{V_T}\right).$

definisco $E_{Fi}(x) - E_F \triangleq q\varphi(x)$

$\hookrightarrow p = n_i \exp\left(\frac{q\varphi(x)}{k_B T}\right); \quad n = n_i \exp\left(-\frac{q\varphi(x)}{k_B T}\right);$

16/02/24

$\hookrightarrow \boxed{\rho = \frac{1}{n\mu_n q} + \frac{1}{p\mu_p q}}$

n e p dipendono da T;

μ_n e μ_p dipendono dal drogaggio;

ciò dipendono da μ;

Alogia

$\alpha_T \equiv \alpha_F$; $\alpha_F = \gamma_F b$;

$I_E = I_{ndiff} + I_{pdiff}$; $\gamma_F = \frac{I_n}{I_n + I_p} \rightarrow I_E = \frac{I_n}{\gamma_F}$

$\hookrightarrow I_E = \frac{I_{ndiff}}{\gamma_F}$; $I_C = I_{nC} + I_{C0} =$

$= b\, I_{ndiff} = \boxed{I_E \gamma_F b}$

$I_D = I_{D0}\left[\exp\left(\frac{V_A}{V_T}\right) - 1\right]$

$\hookrightarrow \frac{\partial I_D}{\partial V_A} = \frac{I_{D0}}{V_T}\exp\left(\frac{V_A}{V_T}\right) = \boxed{\frac{I_D + I_{D0}}{V_T}}$

$V_G = 5V$; $V_S = 2V$; $V_D = 4{,}5V$;

$V_{GS} = 3V$; $V_{th} = 1V \rightarrow V_{GS} - V_{th} = 2V$; $V_{DS} = 2{,}5V$

quadr.

$$W = x_n|V_a| + \sqrt{\left[x_p|V_a|^2\right] - \frac{2\varepsilon_2}{qN_A}\Delta\Phi}$$

$$\to \left[W - x_p|V_a|\right]^2 = x_p^2|V_a|^2 - \frac{2\varepsilon_2}{qN_A}\Delta\Phi$$

$$\hookrightarrow W^2 - 2x_p|V_a|W = -\frac{2\varepsilon_2}{qN_A}\Delta\Phi$$

$$\hookrightarrow x_p|V_a'| = \frac{W}{2} + \frac{\varepsilon_2}{qN_A W'}\Delta\Phi$$

$$\hookrightarrow \cancel{\frac{2(\Phi_i - V_a)}{qN_A^2}\varepsilon N_{eq}} = \boxed{|\Phi_i - V_a| = \left[\frac{W}{2} + \frac{\varepsilon_2}{qN_A W}\Delta\Phi_i\right]^2 \frac{2\varepsilon N_{eq}}{qN_{A_2}^2}}$$

$$\hookrightarrow \cancel{|\Phi_i - V_a| = \left[\frac{W}{2} + \frac{\varepsilon_2}{qN_A W'}\Delta\Phi\right]^2 \cdot \frac{2\varepsilon N_{eq}}{qN_{A2}^2}}$$

Eine Alpensymphonie

Alpine Symphony

Sinfonia delle Alpi

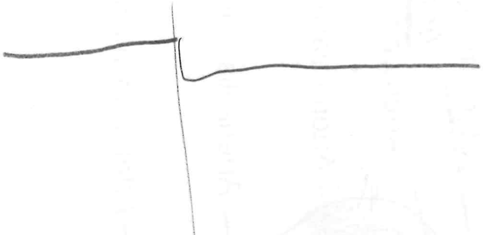
KEINE SYMPHONIE

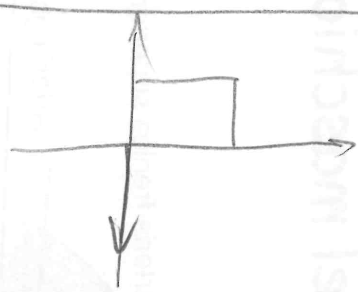
$$q(p - n + N_D - N_A) = \phi \,;$$

$$\hookrightarrow n = \frac{n_i^2}{p} \rightarrow p^2 - (N_A - N_D)\,p - n_i^2 = \phi$$

$$\hookrightarrow \Delta = (N_A - N_D)^2 + 4n_i^2 \,; \quad p = \frac{N_A - N_D}{2} \pm \frac{\sqrt{(N_A - N_D)^2 + 4n_i^2}}{2} =$$

$$p = \frac{N_A - N_D}{2} \pm \sqrt{\left(\frac{N_A - N_D}{2}\right)^2 + 4n_i^2} = \frac{N_A - N_D}{2}\left[1 \pm \sqrt{1 + \frac{4n_i^2}{(N_A - N_D)^2}}\right].$$





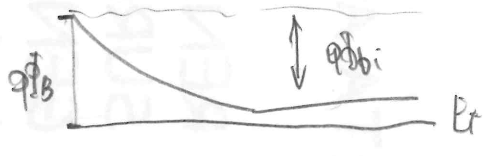
$$\hookrightarrow \Phi_{bi} = \frac{qN_D}{2\varepsilon_s}\, x_d^2 \,;$$

$$E_c(x) = q\Phi_B - \frac{q^2 N_D}{\varepsilon_s}\left[x_d x - \frac{x^2}{2}\right]$$

$$J_{th} = A_\phi T^2 \exp\left(-\frac{q\Phi_B}{K_B T}\right); \qquad I_{SM} \propto n(\phi)\,;$$

$$\hookrightarrow n(\phi) = N_C \exp\left(-\frac{q\Phi_B}{K_B T}\right); \qquad n(\infty) = N_C \exp\left(\frac{E_F - E_C}{K_B T}\right)$$

$$\hookrightarrow n(\phi) = n(\infty) \exp\left(-\frac{q\Phi_B + E_C - E_F}{K_B T}\right)$$



$$= \cancel{n(\infty)}\, N_D \exp\left(-\frac{qV_{bi}}{K_B T}\right).$$