1. Compulsory question.

a)

i) Currents are drift currents. The resistivity of the p-type diffused layer is:

$$\rho = e\mu_p p_p = 1.6\times10^{-19}\times150\times10^{18} = 24\ \Omega\text{cm}$$

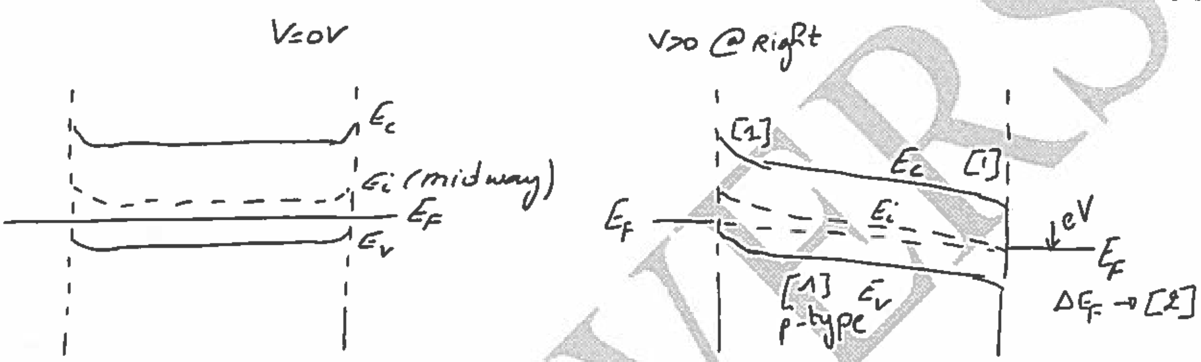
$$R = \frac{\rho L}{A} = \frac{24\times100\times10^{-4}}{10^{-4}\times50\times10^{-4}} = 48\times10^{4}\,\Omega$$ [4]

This expression can be found from the drift-diffusion current densities in the formulae sheet. The conductivity is determined by the majority carriers. The mobility can be estimated from figure 0.

Ohm's law: $V = R_{tot} I$

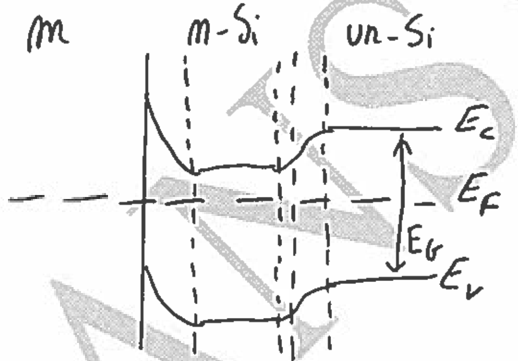
$I = 10^{-3}V/(48\ 10^{4} + 2) = 2.1$ nA.

ii) [5]



b) For a depletion mode GaAs MESFET

i)



[4]

ii) The workfunction of the n-GaAs channel.

$$n = N_c \exp\left(\frac{E_F - E_c}{kT}\right)$$

$$\phi_n = E_c - E_F = kT\ln\left(\frac{N_C}{N_D}\right) = 0.026\ln\left(\frac{4.7\times10^{17}}{10^{17}}\right) = 0.04eV$$

$$\phi_{nGaAs} = \chi_{GaAs} + \phi_n = 4.1 + 0.04 = 4.14eV$$

The built-in voltage due to the Schottky contact:

$$eV_{bi} = 4.6 - 4.14 = 0.46eV$$

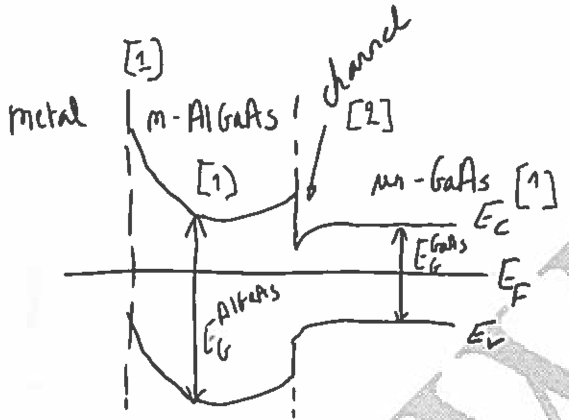
$$W_{depl}(V)=\left[\frac{2\varepsilon_0\varepsilon_{GaAs}(V_{bi}-V)}{eN_D}\right]^{1/2}$$ one-sided junction

-V for fully depleted means $a=W_{depl}(V)=\left[\frac{2\varepsilon_0\varepsilon_{GaAs}(V_{bi}-V)}{eN_D}\right]^{1/2}$

$$-V=\frac{eN_D a^2}{2\varepsilon_0\varepsilon_{GaAs}}-V_{bi}=\frac{1.6\times10^{-19}\times10^{17}\times\left(200\times10^{-7}\right)^2}{2\times13\times8{,}85\times10^{-14}}-0.46V=2.32V \text{ (all in cm)}$$ [5]

d) For a depletion mode AlGaAs/GaAs n-channel HEMT

i)



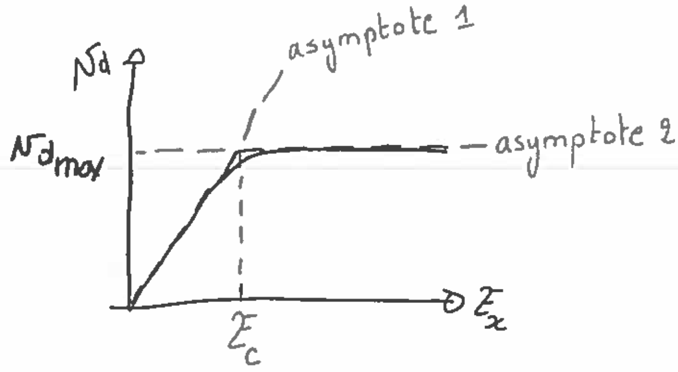
[5]

ii) Because of modulation doping in the HEMT. This means that the doping atoms are separated from the channel and as a result in the channel of a HEMT there is no impurity scattering. The channel of a MESFET is doped and thus impurity scattering occurs. [2]

2. Velocity saturation in short channel Si MOSFETs.

a)

i) [2], ii) [2],



iii) Derive an expression for E_c based on the asymptotes. [2]

asymptote 1: $|v_d| = \mu |E_x|$

asymptote 2: $|v_d| = |v_d^{\max}|$

@ $|E_x| = |E_c|$ the asymptotes cross:

$$|v_d^{\max}| = \mu |E_c|$$

$$|E_c| = \frac{|v_d^{\max}|}{\mu}$$

b)

i) In the linear region. The sign of the current is ignored (should be -1). [8]

$$I_{DS} = WQ_I(x)|v_d(x)| \quad [1]$$

$$I_{DS} = WQ_I(x)|v_d^{\max}| \frac{\left(\frac{|E_x|}{|E_c|}\right)}{\left(1 + \frac{|E_x|}{|E_c|}\right)} \quad [1]$$

$$|E_x| = \frac{dV_{CB}(x)}{dx} \quad [1]$$

$$I_{DS} = WQ_I(x)\left|v_d^{\max}\right| \frac{\left(\dfrac{dV_{CB}/dx}{\left|v_d^{\max}\right|/\mu}\right)}{\left(1+\dfrac{dV_{CB}/dx}{|E_c|}\right)}$$ [1]

$$I_{DS}\left(1+\frac{dV_{CB}/dx}{|E_c|}\right) = W\mu Q_I(x)\, dV_{CB}/dx$$ [1]

$$I_{DS}\left(1+\frac{dV_{CB}/dx}{|E_c|}\right)dx = W\mu Q_I(x)dV_{CB}$$

$$\int_0^L I_{DS}\left(1+\frac{dV_{CB}/dx}{|E_c|}\right)dx = \int_{V_{SB}}^{V_{SB}} W\mu Q_I(x)dV_{CB}$$

$$I_{DS}\left(L+\frac{V_{DB}-V_{SB}}{|E_c|}\right) = W\mu\int_{V_{SB}}^{V_{SB}} C_{ox}(V_{GS}-V_{th}-V_{CB})dV_{CB}$$ [2]

$$I_{DS}\left(L+\frac{V_{DS}}{|E_c|}\right) = W\mu C_{ox}\left[(V_{GS}-V_{th})V_{DS}-\frac{V_{DS}^2}{2}\right]$$

$$I_{DS} = \frac{W\mu C_{ox}}{\left(L+\dfrac{V_{DS}}{|E_c|}\right)}\left[(V_{GS}-V_{th})V_{DS}-\frac{V_{DS}^2}{2}\right]$$ [1]

ii) In the saturation region. [3]

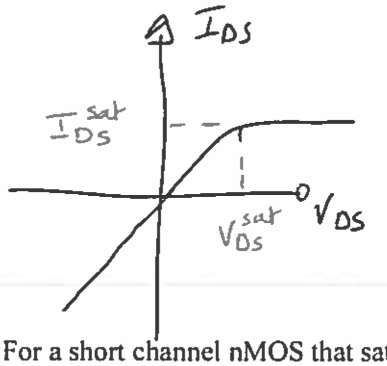
$$I_{DS} = WQ_I(x)\left|v_d^{\max}\right|$$

$$I_{DS} \approx WC_{ox}(V_{GS}-V_{th})\left|v_d^{\max}\right|$$

If we assume that the inversion layer is uniform, thus not dependent on V_{DS} because velocity saturation happens well before pinch off, thus at ~ small V_{DS}.

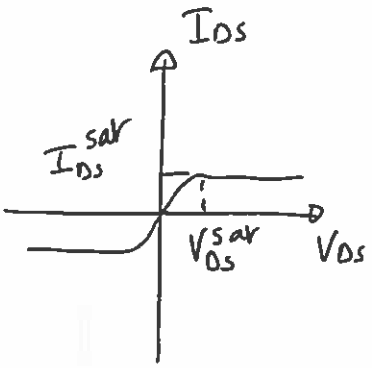
c)

i) For a long channel nMOS that saturates at pinch-off.



[3]

ii) For a short channel nMOS that saturates due to velocity saturation.



[3]

iii) $I_{DS}^{sat}(\text{pinch}-\text{off}) > I_{DS}^{sat}(\text{velocity sat})$
$V_{DS}^{sat}(\text{pinch}-\text{off}) > V_{DS}^{sat}(\text{velocity sat})$ [2]

3. The use of SiGe in current semiconductor device technology.

a) $\chi(x) + E_G(x) =$ constant for $0 \le x \le 0.85$ and gradient starts at x=0 is thus Si.

Thus $\chi(x) + E_G(x) = \chi_{Si} + E_{G\,Si}$

$\chi(x) = \chi_{Si} + E_{G\,Si} - E_G(x)$

$\chi(x) = 4.05 + 1.12 - (1.12 - 0.41 \times x) = 4.05 + 0.41 \times x$

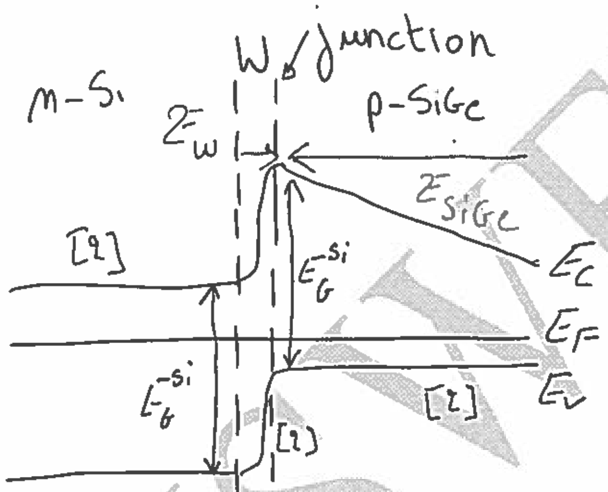
Thus the position of the bands with respect to the vacuum level in SiGe is:

$E_c(x) = \chi(x) = 4.05 + 0.41 \times x$ [2]

$E_v(x) = \chi(x) + E_G(x) = 4.05 + 0.41 \times x + 1.12 - 0.41 \times x = 5.17eV$ [2]

$E_c(0) = 4.05;\quad E_c(0.85) = 4.05 + 0.41 \times 0.85 \approx 4.4eV$

$N_D = 10^{-3} \times N_A \rightarrow$ depletion stretches into the n-Si layer (lowest doping). [10]



b) in depletion region and SiGe layer, directions are opposite and pointing towards increasing energy. [5]

c) Write the expression of the minority carrier current density in both the Si as well as the $Si_{1-x}Ge_x$ region if a forward bias, V_a is applied across the diode in a). The mathematical expressions should be written as a function of material parameters: N_A, N_D, D_p, D_m, x and applied voltage. You should assume that V_a drops across the junction depletion region only. Hint: look at the formulae sheet. [10]

Minority carrier current in the n-Si region is due to holes and is determined by diffusion (no electric field in the quasi-neutral region.

$$I_p = \frac{eD_p p_n}{L_p}\left(e^{\frac{eV_a}{kT}} - 1\right)A = \frac{eD_p n_i^2}{L_p N_D}\left(e^{\frac{eV_a}{kT}} - 1\right)A \quad [2]$$

Minority carrier current in the p-region is due to electrons. Since the SiGe is graded, there is both diffusion as well as drift. The diffusion is due to carrier injection across the junction, drift is due to the internal electric field that is a consequence of the Ge gradient. Both are in the same direction.

The drift component

$$E(x) = -\frac{dE_c(x)}{dx} \quad [2]$$

@ x = 0 → E_c = 0 eV, @ x = L → E_c = -0.41 eV (change of zero point)

$$E_c(x) = \frac{-0.41}{L}x \quad [2]$$

$$E = \frac{0.41}{L}$$

$$I_n^{drift} = e\mu_n n(x)E(x)A = \mu_n Q_n E$$

$$Q_n = eA\int_0^L n_{p_0}\exp\left(\frac{V_a}{V_T}\right)\exp\left(\frac{-x}{L_n}\right)dx = eAn_{p_0}\exp\left(\frac{V_a}{V_T}\right)\int_0^\infty \exp\left(\frac{-x}{L_n}\right)dx = eAn_{p_0}L_n\exp\left(\frac{V_a}{V_T}\right)$$

[2]

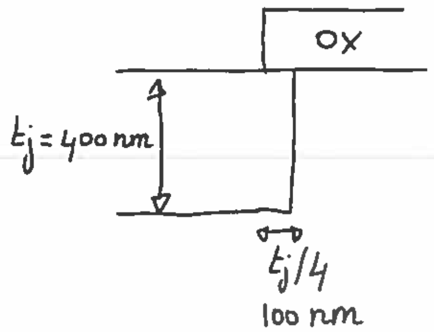
$$I_n^{drift} = 0.41eA\mu_n n_{p_0}\frac{L_n}{L}\exp\left(\frac{V_a}{V_T}\right)$$

$$I_n = 0.41eA\mu_n n_{p_0}\frac{L_n}{L}\exp\left(\frac{V_a}{V_T}\right) + \frac{eD_n n_p}{L_n}\left(e^{\frac{eV}{kT}} - 1\right)A \quad [2]$$

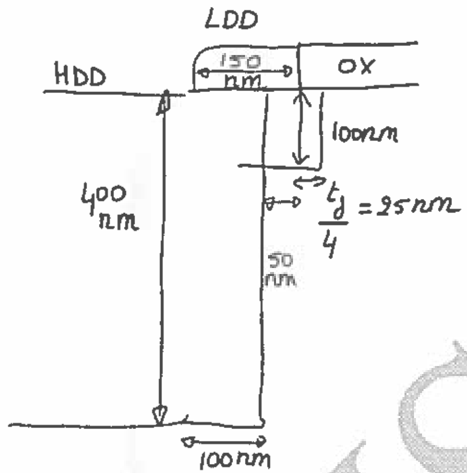
$$I_n = 0.41eA\mu_n n_{p_0}\frac{L_n}{L}\exp\left(\frac{V_a}{V_T}\right) + \frac{eD_n n_i^2}{L_n N_A}\left(e^{\frac{eV}{kT}} - 1\right)A$$

4. The influence of the access resistance in MOSFETs.

a) i) [5]



ii) [6]



(Do not use red or green ink on your exam scripts)

b) The expression for the strong inversion current in a MOSFET in the linear region. $V_{DS} < V_{GS}-V_{th}$ -> linear region.

$$I_{DS} = \frac{\mu C_{ox} W}{L}(V_{GS} - V_{th})V_{DS}$$

$$I_{DS} = \frac{400 \times 4 \times 8.85 \times 10^{-14} \times 5 \times 10^{-4}}{4 \times 10^{-7} \times 800 \times 10^{-7}}(V_{GS} - V_{th})V_{DS}$$ [2]

$$I_{DS} = 2.21 \times 10^{-3} \times (V_{GS} - V_{th})V_{DS}$$

$$I_{DS} = K(V_{GS} - V_{th})V_{DS}$$

V_{GS} and V_{DS} in this formulae are the externally applied voltages minus the voltage drop across the parasitic resistances:

$V_{DS} = V_{DSext} - R_{tot}\, I_{DS}$ [2]

$V_{GS} = V_{GSext} - R_{tot}/2\, I_{DS}$

$$I_{DS} = K(V_{GS} - V_{th})V_{DS}$$

$$I_{DS} = K\left(V_{GS_{ext}} - V_{th} - \frac{R_{tot}}{2} I_{DS}\right)\left(V_{DS_{ext}} - R_{tot} I_{DS}\right)$$

$$I_{DS} = K\left[\left(V_{GS_{ext}} - V_{th}\right)V_{DS_{ext}} - \frac{R_{tot}}{2} I_{DS} V_{DS_{ext}} - \left(V_{GS_{ext}} - V_{th}\right)R_{tot} I_{DS} + \frac{R_{tot}^2}{2} I_{DS}^2\right]$$ [4]

$$I_{DS} = K\left[\left(V_{GS_{ext}} - V_{th}\right)V_{DS_{ext}} - \frac{R_{tot}}{2} I_{DS} V_{DS_{ext}} - \left(V_{GS_{ext}} - V_{th}\right)R_{tot} I_{DS} + \frac{R_{tot}^2}{2} I_{DS}^2\right]$$

$$0 = \left[\left(V_{GS_{ext}} - V_{th}\right)V_{DS_{ext}} - \left(\frac{1}{K} + \frac{R_{tot}}{2} V_{DS_{ext}} - R_{tot}\left(V_{GS_{ext}} - V_{th}\right)\right) I_{DS} + \frac{R_{tot}^2}{2} I_{DS}^2\right]$$

i) For self-aligned HDD implant. [2]

$$0 = \left[(1-0.4)0.1 - \left(\frac{1}{2.21\times10^{-3}} + \frac{1.24}{2}0.1 - 1.24(1-0.4)\right) I_{DS} + \frac{(1.24)^2}{2} I_{DS}^2\right]$$

$$0 = \left[0.06 - 452.8\times I_{DS} + 0.77\times I_{DS}^2\right]$$

$$I_{DS} = \frac{452.8 - \sqrt{452.8^2 - 4\times0.77\times0.06}}{2\times0.77} = 1.33\times10^{-4} A$$

Note that the sign is determined by the fact that the current should reduce.

ii) for side wall spacer technology [2]

$$0 = \left[(1-0.4)0.1 - \left(\frac{1}{2.21\times10^{-3}} + \frac{24.68}{2}0.1 - 24.68(1-0.4)\right) I_{DS} + \frac{(24.68)^2}{2} I_{DS}^2\right]$$

$$0 = \left[0.06 - 468\times I_{DS} + 305\times I_{DS}^2\right]$$

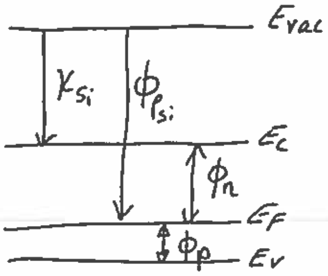
$$I_{DS} = \frac{468 - \sqrt{468^2 - 4\times305\times0.06}}{2\times305} = 1.28\times10^{-4} A$$

c) Reduced DIBL (apparent at higher V_{DS}), reduced parasitic overlap capacitance, better control of L_{eff}. [2]

5.

a) [5]

Calculate work function of Si from

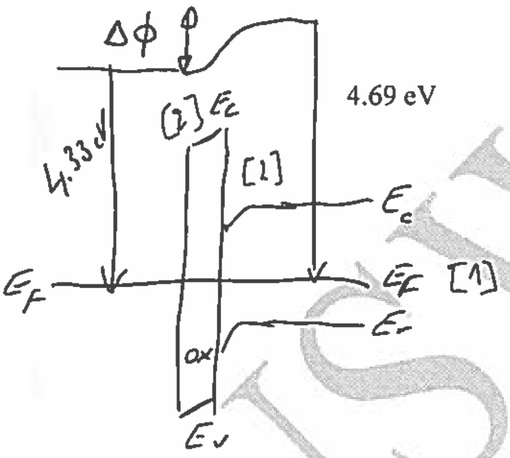


$$\phi_{pSi} = \phi_n + \chi_{Si}$$

$$\phi_{pSi} = E_c - E_F = kT\ln\left(\frac{N_c}{n_p}\right) = kT\ln\left(\frac{N_c N_A}{n_i^2}\right) = 0.026\ln\left(\frac{2.8\times10^{19}\times10^{16}}{\left(1.45\times10^{10}\right)^2}\right) \approx 0.91eV$$

$$\phi_{pSi} = 0.91 + 4.05 = 4.96eV$$

$$\phi_{Ti} = 4.33eV$$



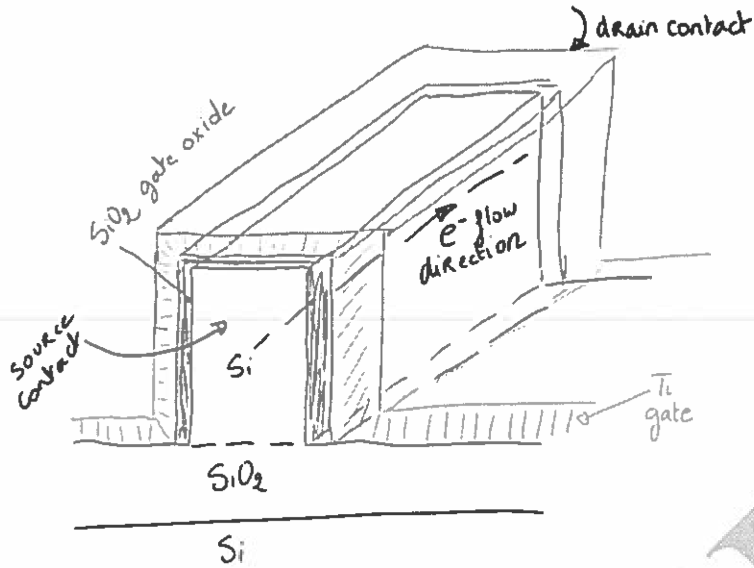
b) Contact potential: $\Delta\phi = \phi_{pSi} - \phi_{Ti} = 4.96 - 4.33 = 0.63eV$ in voltage: 0.63 V. 1/5th of the contact potential difference is dropped across the oxide layer thus across Si: $V_s \approx 0.5$ V. Depletion width 1-sided junction (formulae sheet): [2] [5]

$$W_{depl}(V) = \left[\frac{2\varepsilon(V_{bi} - V)}{e}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)\right]^{1/2}$$

$$W_{depl}(0) = \left[\frac{2\varepsilon_0\varepsilon_{Si}V_{bi}}{eN_A}\right]^{1/2} \quad [3]$$

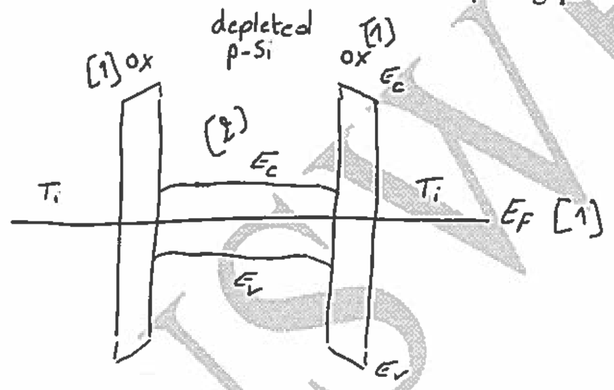
$$W_{depl}(0) = \sqrt{\frac{2\times8.85\times10^{-14}\times12\times0.5}{1.6\times10^{-19}\times10^{16}}} = 2.6\times10^{-5}\,cm = 260nm$$

c)



[5]

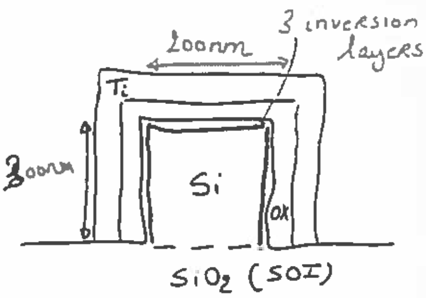
d) The fin is completely depleted (see b). [5]
depletion can be indicated by an intrinsic material as seen for the operation regions of a MOSFET. There should be a voltage drop across the oxides. Within the pSi it should be flat or with little bends at the interface and E_F midgap.



e) 3 channels with different widths
the total width is 2 × H + W = 800 nm. [2] [5]
Total current (is through all 3 channels):

$$I_n^{drift} = \mu_n Q_n W E = \mu_n Q_n W \frac{V_{DS}}{L} \quad [3]$$

$$I_n^{drift} = \frac{1200}{2}\frac{\text{cm}^2}{\text{Vs}} \times 5\times10^{-7}\frac{C}{\text{cm}^2} \times 800\times10^{-7}\,\text{cm}\frac{10^{-3}\,\text{V}}{400\times10^{-7}\,\text{cm}} = 15\times10^{-8}\,A$$



The mobility is taken from the graph in the formulae and constants sheets.