

1. Compulsory question.

a)

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

$$\rho = e\mu_p p_p = 1.6 \times 10^{-19} \times 150 \times 10^{18} = 24 \Omega\text{cm}$$

$$R = \frac{\rho L}{A} = \frac{24 \times 100 \times 10^{-4}}{10^{-4} \times 50 \times 10^{-4}} = 48 \times 10^4 \Omega \quad [4]$$

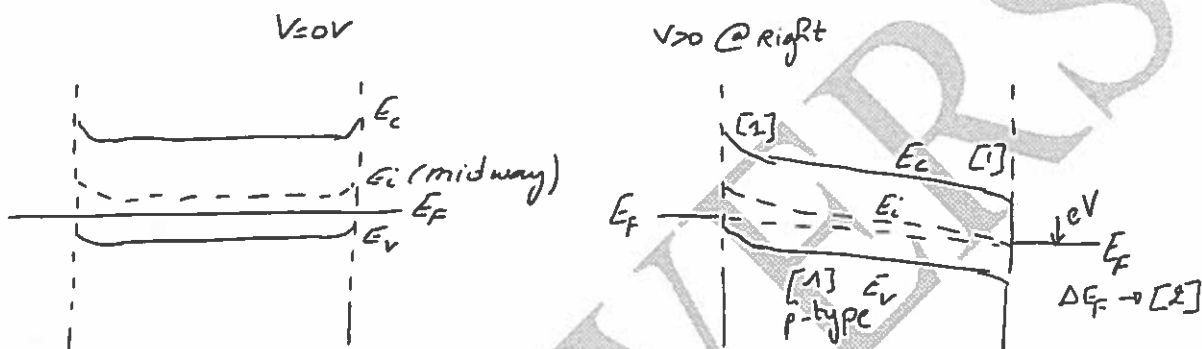
This expression can be found from the drift-diffusion current densities in the formulae sheet. The conductivity is determined by the majority carriers. The mobility can be estimated from figure 0.

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

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

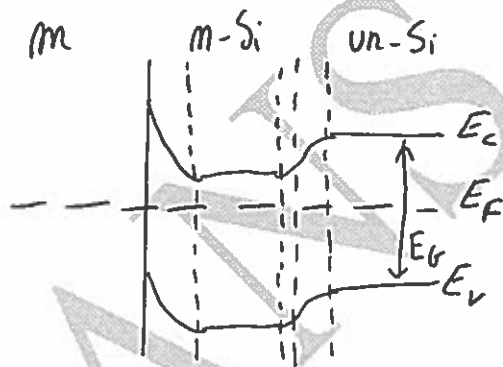
ii)

[5]



b) For a depletion mode GaAs MESFET

i)



[4]

ii) The workfunction of the n-GaAs channel.

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

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

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

The built-in voltage due to the Schottky contact:

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

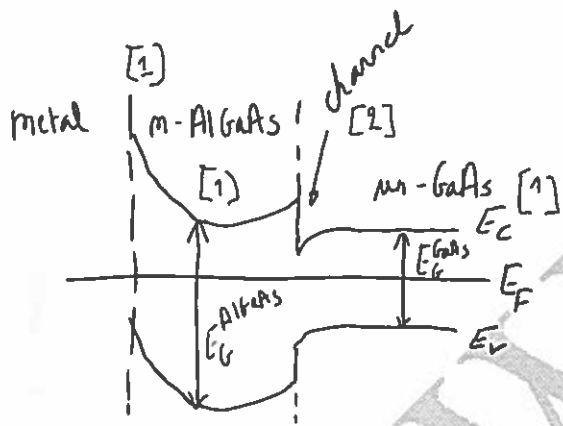
$$W_{depl}(V) = \left[ \frac{2\epsilon_0\epsilon_{GaAs}(V_{bi} - V)}{eN_D} \right]^{1/2} \text{ one-sided junction}$$

$$-V \text{ for fully depleted means } a = W_{depl}(V) = \left[ \frac{2\epsilon_0\epsilon_{GaAs}(V_{bi} - V)}{eN_D} \right]^{1/2}$$

$$-V = \frac{eN_D a^2}{2\epsilon_0\epsilon_{GaAs}} - V_{bi} = \frac{1.6 \times 10^{-19} \times 10^{17} \times (200 \times 10^{-7})^2}{2 \times 13 \times 8.85 \times 10^{-14}} - 0.46V = 2.32V \text{ (all in cm)} \quad [5]$$

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

i)



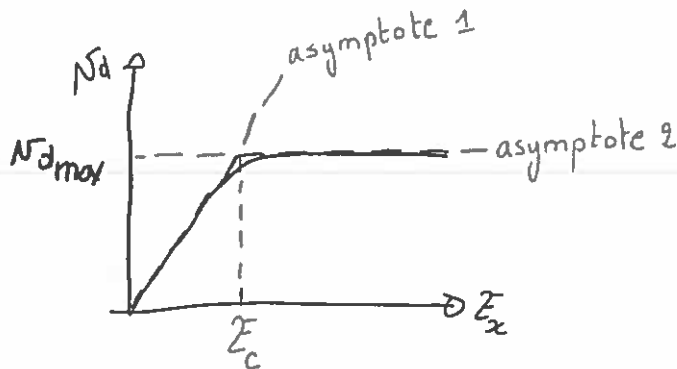
[5]

- 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:  $|v_d| = |v_d^{\max}|$

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

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

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

b)

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

[8]

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

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

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

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

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

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

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

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

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

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

ii) In the saturation region.

[3]

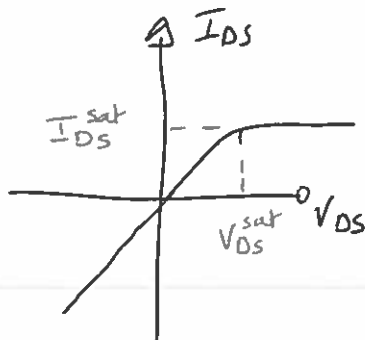
$$I_{DS} = WQ_I(x) \left| v_d^{\max} \right|$$

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

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  $\sim$  small  $V_{DS}$ .

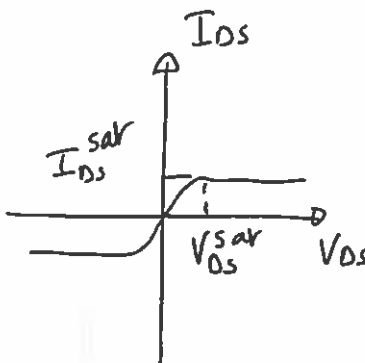
c)

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

[2]

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

- a)  $\chi(x) + E_G(x) = \text{constant}$  for  $0 \leq x \leq 0.85$  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:

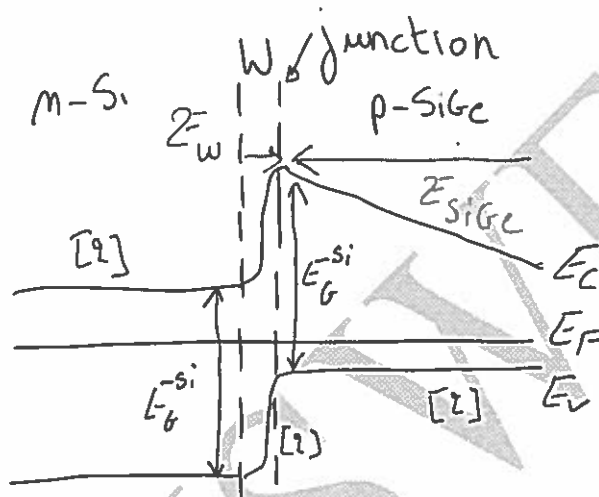
$E_c(x) = \chi(x) = 4.05 + 0.41 \times x$  [1]

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

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

$N_D = 10^{-3} \times N_A \rightarrow$  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  $\text{Si}_{1-x}\text{Ge}_x$  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:  $N_A$ ,  $N_D$ ,  $D_p$ ,  $D_n$ ,  $x$  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).

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

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

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

@  $x = 0 \rightarrow E_c = 0 \text{ eV}$ , @  $x = L \rightarrow E_c = -0.41 \text{ eV}$  (change of zero point)

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

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

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

$$Q_n = eA \int_0^L n_{p_0} \exp\left(\frac{V_a}{V_T}\right) \exp\left(\frac{-x}{L_n}\right) dx = eAn_{p_0} \exp\left(\frac{V_a}{V_T}\right) \int_0^L \exp\left(\frac{-x}{L_n}\right) dx = eAn_{p_0} L_n \exp\left(\frac{V_a}{V_T}\right) \quad [2]$$

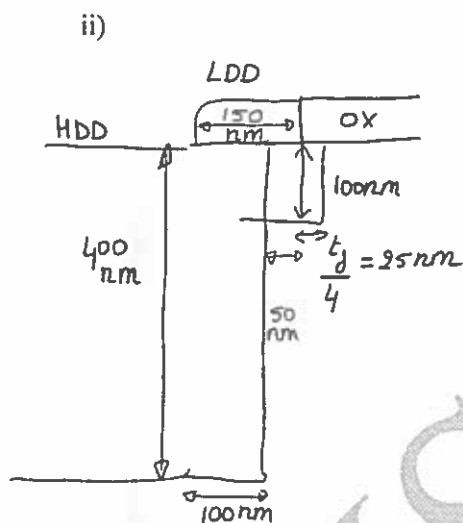
$$I_n^{drift} = 0.41 eA \mu_n n_{p_0} \frac{L_n}{L} \exp\left(\frac{V_a}{V_T}\right)$$

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

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

[5]

[6]



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

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

$$V_{GS} = V_{GSext} - R_{lot}/2 I_{DS}$$



$$\begin{aligned}
I_{DS} &= K(V_{GS} - V_{th})V_{DS} \\
I_{DS} &= K\left(V_{GS_{eff}} - V_{th} - \frac{R_{tot}}{2}I_{DS}\right)(V_{DS_{eff}} - R_{tot}I_{DS}) \\
I_{DS} &= K\left[(V_{GS_{eff}} - V_{th})V_{DS_{eff}} - \frac{R_{tot}}{2}I_{DS}V_{DS_{eff}} - (V_{GS_{eff}} - V_{th})R_{tot}I_{DS} + \frac{R_{tot}^2}{2}I_{DS}^2\right] \\
I_{DS} &= K\left[(V_{GS_{eff}} - V_{th})V_{DS_{eff}} - \frac{R_{tot}}{2}I_{DS}V_{DS_{eff}} - (V_{GS_{eff}} - V_{th})R_{tot}I_{DS} + \frac{R_{tot}^2}{2}I_{DS}^2\right] \\
0 &= \left[(V_{GS_{eff}} - V_{th})V_{DS_{eff}} - \left(\frac{1}{K} + \frac{R_{tot}}{2}V_{DS_{eff}} - R_{tot}(V_{GS_{eff}} - V_{th})\right)I_{DS} + \frac{R_{tot}^2}{2}I_{DS}^2\right]
\end{aligned} \tag{4}$$

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

$$\begin{aligned}
0 &= \left[(1-0.4)0.1 - \left(\frac{1}{2.21 \times 10^{-3}} + \frac{1.24}{2}0.1 - 1.24(1-0.4)\right)I_{DS} + \frac{(1.24)^2}{2}I_{DS}^2\right] \\
0 &= [0.06 - 452.8 \times I_{DS} + 0.77 \times I_{DS}^2] \\
I_{DS} &= \frac{452.8 - \sqrt{452.8^2 - 4 \times 0.77 \times 0.06}}{2 \times 0.77} = 1.33 \times 10^{-4} A
\end{aligned}$$

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

ii) for side wall spacer technology [2]

$$\begin{aligned}
0 &= \left[(1-0.4)0.1 - \left(\frac{1}{2.21 \times 10^{-3}} + \frac{24.68}{2}0.1 - 24.68(1-0.4)\right)I_{DS} + \frac{(24.68)^2}{2}I_{DS}^2\right] \\
0 &= [0.06 - 468 \times I_{DS} + 305 \times I_{DS}^2] \\
I_{DS} &= \frac{468 - \sqrt{468^2 - 4 \times 305 \times 0.06}}{2 \times 305} = 1.28 \times 10^{-4} A
\end{aligned}$$

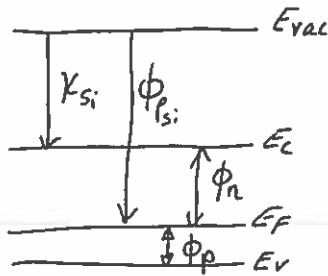
c) Reduced DIBL (apparent at higher  $V_{DS}$ ), reduced parasitic overlap capacitance, better control of  $L_{eff}$ . [2]

5.

a)

[5]

Calculate work function of Si from

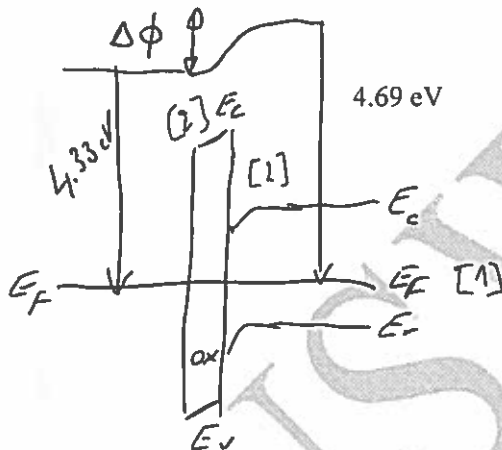


$$\phi_{pSi} = \phi_n + \chi_{Si}$$

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

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

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



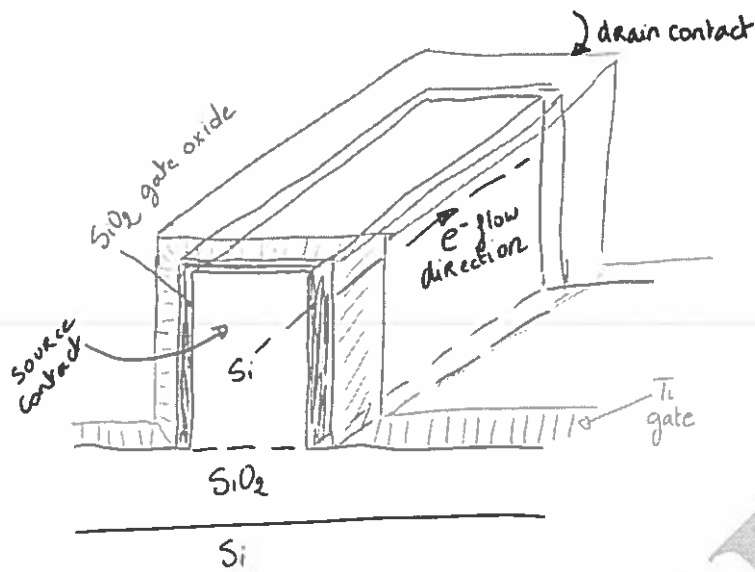
- b) Contact potential:  $\Delta\phi = \phi_{pSi} - \phi_{Ti} = 4.96 - 4.33 = 0.63 \text{ eV}$  in voltage: 0.63 V. 1/5<sup>th</sup> of the contact potential difference is dropped across the oxide layer thus across Si:  $V_s \approx 0.5 \text{ V}$ . Depletion width 1-sided junction (formulae sheet):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

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

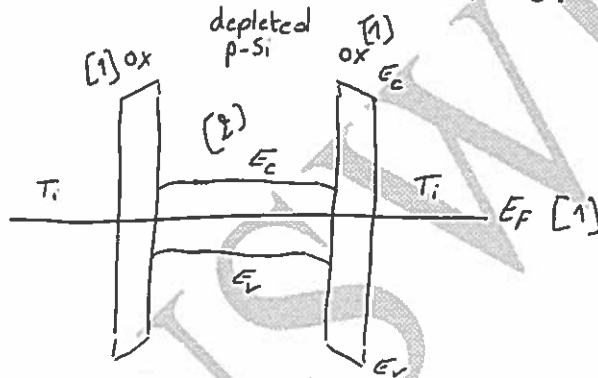
$$W_{depl}(0) = \left[ \frac{2\epsilon_0\epsilon_{Si}V_{bi}}{eN_A} \right]^{1/2} \quad [3]$$

$$W_{depl}(0) = \sqrt{\frac{2 \times 8.85 \times 10^{-14} \times 12 \times 0.5}{1.6 \times 10^{-19} \times 10^{16}}} = 2.6 \times 10^{-5} \text{ cm} = 260 \text{ nm}$$

c)



- 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. [5]



- e) 3 channels with different widths  
the total width is  $2 \times H + W = 800 \text{ nm}$ . [1]  
Total current (is through all 3 channels):

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

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

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

