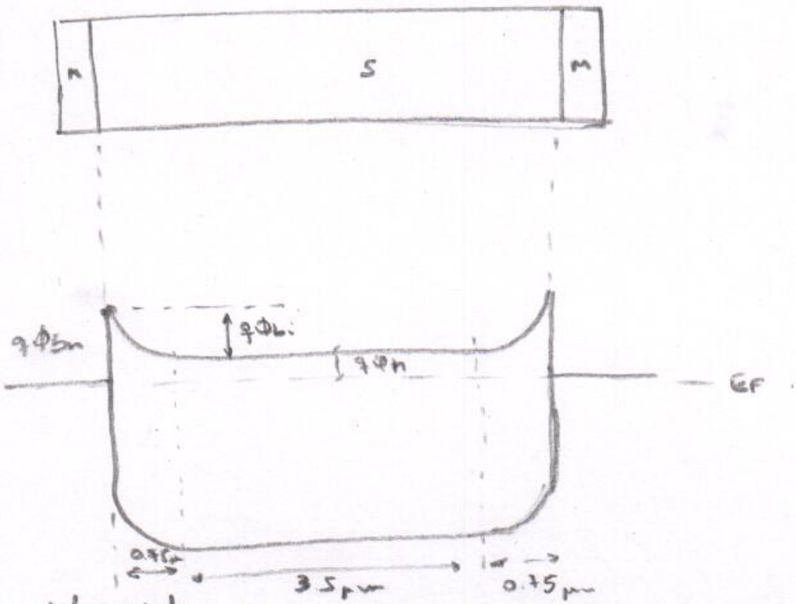
Exercice 4

$N_D = 10^{15}\ cm^{-3}$

$q\varphi_{bn} = 0.7\,eV$

a) $t = 5\mu m$



$q\Phi_{bi} = W_M - W_S$

$q\varphi_{bn} = W_M - \chi_S = q\Phi_{bi} + q\varphi_n$

• $q\varphi_n = E_c - E_F = kT\ \ln\left(\frac{N_c}{N_D}\right) = 0.026\ \ln\left(\frac{2.9\times10^{19}}{10^{15}}\right) = 0.27\,eV$

• $q\Phi_{bi} = q\varphi_{bn} - q\varphi_n = 0.7 - 0.27 = 0.43\,eV$

• $x_d = \sqrt{\frac{2.\varepsilon.\Phi_{bi}}{q.N_D}} = \sqrt{\frac{2.\ 11.7.\ 8.85\times10^{-14}\times0.43}{1.6\times10^{-19}\times10^{15}}} = 7.46\times10^{-5}\,cm = \underline{0.75\,\mu m}$

a) $t = 5\mu m$

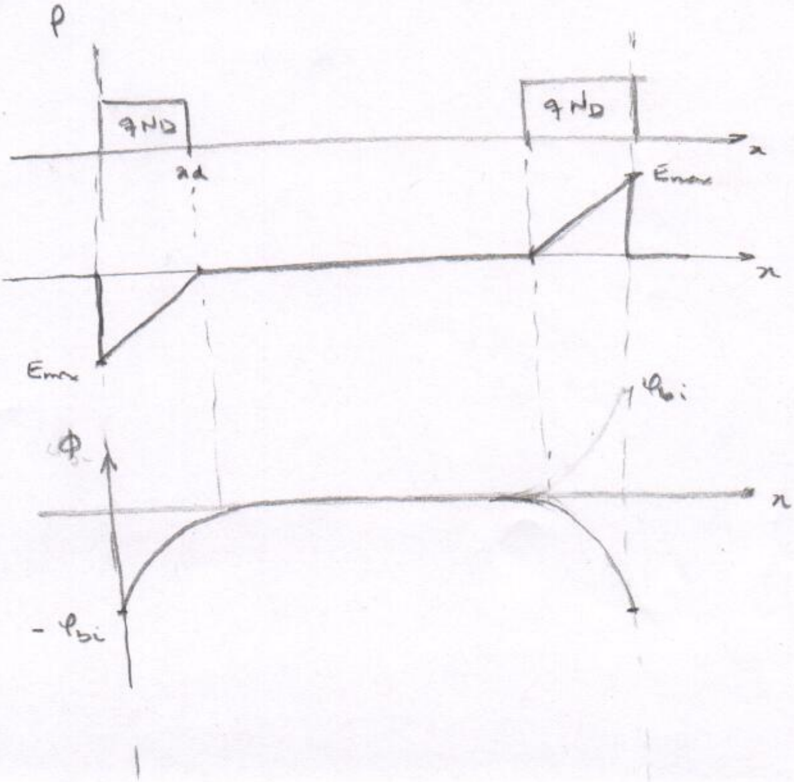
$n(t/2) = N_D = 10^{15}\ cm^{-3}$

$p(t/2) = \frac{n_i^2}{n} = 10^5\ cm^{-3}$

$E(t/2) = 0 \rightsquigarrow$ bands are flat!

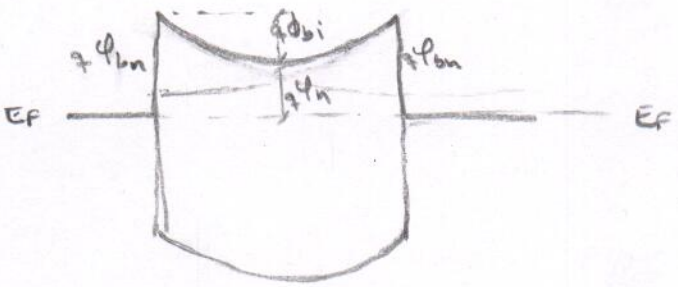
$|E_{max}| = \frac{q\ N_D\ .\ x_d}{\varepsilon} = 1.15\times10^4\ V/cm$

$\frac{d\Phi}{dx} = -E$



b) $t = 1\mu m$

Since $x_d = 0.7\,\mu m$ $\Rightarrow$ semiconductor is fully depleted!



$$q\phi_{bi} = \underbrace{q\varphi_{bn}}_{\text{fixed}} - \underbrace{q\varphi_n}_{?}$$

$\rho = qN_D$ since it is fully depleted.

From Gauss law:

$$\frac{dE}{dx} = \frac{\rho}{\varepsilon} = \frac{qN_D}{\varepsilon} \Rightarrow \int_{E(0)}^{E(x)} dE = \int_0^x \frac{qN_D}{\varepsilon}\,dx \Rightarrow \boxed{E(x) - E(0) = \frac{qN_D}{\varepsilon}x}$$

then, the potential:

$$\frac{d\phi}{dx} = -E = -\frac{qN_D}{\varepsilon}x - E(0)$$

$$\therefore \phi(x) - \phi(0) = -E(0)\cdot x - \frac{qN_D}{2\varepsilon}\cdot x^2$$

Side note:

if $t > x_d$, for $x = x_d$:

$$\phi(x_d) = -\frac{qN_D}{2\varepsilon}\cdot\frac{2\varepsilon}{qN_D}\phi_{bi}$$

$$\therefore \boxed{\phi(x_d) - \phi(0) = -\phi_{bi}}$$

But due to symmetry $E(x = t/2) = 0$.

$$E(x) = E(0) + \frac{qN_D}{\varepsilon}\cdot x \Rightarrow E(0) = -\frac{qN_D}{\varepsilon}t/2$$

thus:

$$E(x) = \frac{qN_D}{\varepsilon}(x - t/2)$$

$$\phi(x) - \phi(0) = \frac{qN_D}{\varepsilon}\frac{t}{2}\cdot x - \frac{qN_D}{\varepsilon}\cdot\frac{x^2}{2}$$

$\therefore$ at $x = t/2 \Rightarrow \Delta\phi = \phi(t/2) - \phi(0) = \phi_{bi}$

$$\therefore \phi_{bi} = \frac{qN_D}{\varepsilon}\left(\frac{t}{2}\right)^2 - \frac{qN_D}{2\varepsilon}(t/2)^2 = \frac{1}{2}\frac{qN_D}{\varepsilon}\cdot\Big(\underbrace{\frac{t}{2}}_{1\times10^{-4}cm}\Big)^2 = 0.19\,V$$

$$q\Phi_{bi} = \underbrace{q\varphi_{bn}}_{0.7} - q\varphi_n \Rightarrow \varphi_n = \varphi_{bn} - \Phi_{bi} = 0.51\,V$$

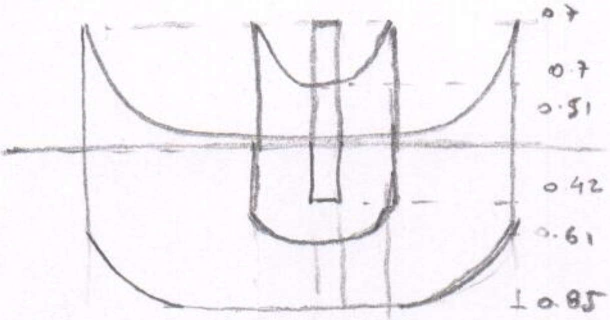
$$0.7 - 0.19$$

$$\therefore n = N_c \times \exp\left(-\frac{0.51}{kT}\right) = 3.8\times10^{10}\,cm^{-3}$$

$$p = \frac{n_i^2}{n} = 1.14\times10^{9}\,cm^{-3}$$

n is decreasing in the center.

case c: $t \to \infty$



$E(t,z) = 0$

$\Phi_{bi} \to 0$

$\varphi_n \to \varphi_{bn} = 0.7$

$$n = N_c \cdot \exp\left(-\frac{0.7}{kT}\right) = 5.87\times10^{7}\,cm^{-3}$$

$$p = \frac{n_i^2}{n} = 1.7\times10^{12}\,cm^{-3}$$

inversion!

Case c: $t \rightarrow 0$ still totally depleted

$E(t/2) = 0$ independent of t

$$\phi(t/2) = \phi(0) + \frac{qN_D}{2\varepsilon}\cdot\left(\frac{t}{2}\right)^2 \xrightarrow[t \to 0]{} \phi(t/2) \rightarrow \phi(0) = -0.43V$$

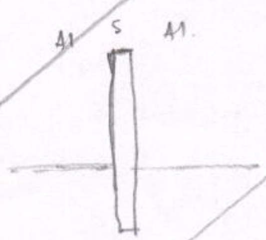
$$n(t/2) = N_D \cdot \exp\left(\frac{q\,\overset{-0.43V}{\phi(t/2)}}{kT}\right) = 5.87 \times 10^{7}\ cm^{-3} \Rightarrow q\varphi_n = 0.7\ eV$$

$$n_i^2/n(t/2) = 2.0 \times 10^{12}\ cm^{-3}$$

p is larger than n! $\Rightarrow$ inversion layer imposed by metals.

$\phi_{bi} = 0 \Rightarrow$ no barrier for electrons to flow

however, no more electrons.



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2) $A = 20 \times 20\ \mu m^2$

$\phi_{bi} = \varphi_{b_n} - \varphi_n$

$$1/C_j(V)^2 = (\phi_{bi} - V)\cdot\frac{1}{A^2}\cdot\frac{2}{\varepsilon_{Si}\, q N_D}$$

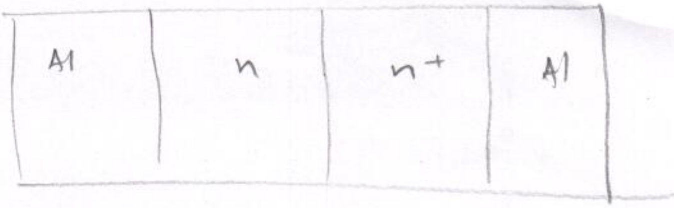
from the slope $\Rightarrow N_D$

$N_D = 1.1 \times 10^{16}\ cm^{-3}$

$$\phi_{bi} \Rightarrow C(V=0) \qquad \frac{1}{C_j^2(0)} = \phi_{bi}\cdot\frac{1}{A^2}\cdot\frac{2}{\varepsilon_{Si}\, qN} = 0.86V$$

$$\varphi_{bn} = \phi_{bi} + \varphi_n = 0.86 + \underbrace{kT \ln\left(\frac{N_C}{N_D}\right)}_{0.2} = 1.06V$$

3)



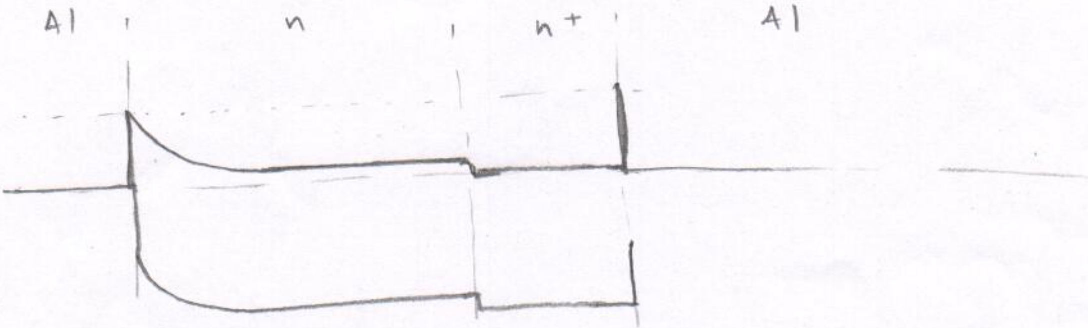
a) First, we calculate $|E_c - E_F|$ in both semiconductors

$$q\varphi_n = KT \ln\left(\frac{N_c}{N_D}\right) = 0.026 \ln\left(\frac{2.9\times10^{19}}{1\times10^{16}}\right) = 0.21\,eV$$

$$q\varphi_{n^+} = KT \ln\left(\frac{N_c}{N_D}\right) = 0.026 \ln\left(\frac{2.9\times10^{19}}{1\times10^{19}}\right) = 0.03\,eV$$

Depletion regions:

$$\frac{x_d^{\,n}}{x_d^{\,n^+}} = \frac{\sqrt{(2\varepsilon_{si}\,\phi_{bi}^{n})/qN_D}}{\sqrt{(2\varepsilon_{si}\,\phi_{bi}^{n^+})/qN_D}} = \frac{33\,nm}{1\,nm} \approx 33$$



$q\varphi_{bn} = 0.68\,eV$

$$\phi_{bi}^{Al\text{-}n} = \varphi_{bn} - \varphi_n = 0.68 - 0.21 = 0.47\,V$$

$$\phi_{bi}^{n^+\text{-}Al} = \varphi_{bn} - \varphi_{n^+} = 0.68 - 0.03 = 0.65\,V$$ (Don't be misled)

Ohmic by tunneling.

$$\phi_{bi}^{n\text{-}n^+} = 0.21 - 0.03 = 0.18\,V$$