2.1 a) $n_i = 1{,}66 \times 10^{15}\, T^{3/2} \exp \frac{-E_g}{2KT}$ cm^{-3} , $E_g = 0{,}66$ eV
$K = 1{,}38 \times 10^{-23}$ J/K

p/ T = 300K , $n_i = 1{,}66 \times 10^{15} \times 300^{3/2} \exp\left(\frac{-0{,}66\ eV}{2 \times 1{,}38 \times 10^{-23} J/K \times 300}\right)$

$1\,eV = 1{,}6 \times 10^{-19} J \rightarrow 0{,}66\,eV = 1{,}056 \times 10^{-19} J$

$n_i = 1{,}66 \times 10^{15} \times 300^{3/2} \exp\left(\frac{-1{,}056 \times 10^{-19}}{2 \times 1{,}38 \times 10^{-23} \times 300}\right)$

$n_i = 2{,}4944 \times 10^{13}$ eletrons/cm^3

p/ T = 600K , $n_i = 4{,}1488 \times 10^{16}$ eletrons/cm^3

• Pode-se observar que a densidade de eletrons do germanio é maior que no silício.

Para Si → T = 300K , $n_i = 1{,}08 \times 10^{10}$ eletrons/cm^3
T = 600K, $n_i = 1{,}54 \times 10^{13}$ eletrons/cm^3

b) $n\,p = n_i^2$ $p = 5 \times 10^{16}\ cm^{-3}$ → dopado de lacunas

$n = \frac{n_i^2}{p}$ - concentração de eletrons $p = 5 \times 10^{16}\ cm^{-3}$ → concentração de lacunas

p/ T = 300K → $n = \frac{(2{,}4944 \times 10^{13})^2}{5 \times 10^{16}} = 1{,}2444 \times 10^{10}\ cm^{-3}$ e $p = 5 \times 10^{16}\ cm^{-3}$

p/ T = 600K → $n = \frac{(4{,}1488 \times 10^{16})^2}{5 \times 10^{16}} = 3{,}4425 \times 10^{16}\ cm^{-3}$ e $p = 5 \times 10^{16}\ cm^{-3}$

2.2 $E = 0{,}1\ V/\mu m$ - tipo n - silício

a) eletron: $\vec{v_e} = -\mu_n \vec{E}$, onde $\mu_n = 1350\ cm^2/V.s$

$|v_e| = 1350 \times (10^{-2})^2 \frac{m^2}{V.s} \times 0{,}1 \frac{V}{10^{-6} m} = 13.5 \times 10^3\ m/s$

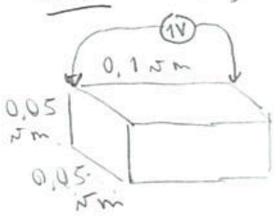
lacuna $\vec{v_h} = \mu_h \vec{E}$, onde $\mu_h = 480 \frac{cm^2}{V.s}$

$|v_h| = 480 \times (10^{-2})^2 \frac{m^2}{V.s} \times \frac{0{,}1 V}{10^{-6} m} = 4.8 \times 10^3\ m/s$

b) $J_n = \mu_n . E . n . q = 1 \frac{mA}{\mu m^2}$

$J_n = 1350 \times (10^{-2})^2 \frac{m^2}{V.s} \times 0{,}1 \frac{V}{10^{-6} m} \times 1{,}6 \times 10^{-19}\ C \times n = 1 \frac{mC/s}{\mu m^2}$ → $\boxed{n = 4{,}6296 \times 10^{17} \frac{eletrons}{m^3}}$

2.3   Si, tipo N, $\ell = 0{,}1\ \mu m$



a) $N = 10^{17}\ cm^{-3}$ $n_i = 1{,}08 \times 10^{10}$ electrons$/cm^3$

$T = 300\ K$

$$p = \frac{n_i^2}{N} = \frac{(1{,}08 \times 10^{10})^2}{10^{17}} = 1{,}166 \times 10^{3}\ cm^{-3}$$

$J_{tot} = q(\mu_N N + \mu_h p) E$, onde $\mu_N = 1350\ \frac{cm^2}{Vs}$, $\mu_h = 480\ \frac{cm^2}{Vs}$

$$J_{tot} = 1{,}6 \times 10^{-19}\ C \times \left(1350 \times \frac{cm^2}{Vs} \cdot 10^{17} \frac{1}{cm^3} + 480 \frac{cm^2}{Vs} \cdot 1{,}166 \times 10^{3} \frac{1}{cm^3}\right) \times \frac{1\ V}{10^{-5} \times cm}$$

$$J_{tot} = 135 \times 10^{4}\ \frac{A}{cm^2}$$

$$I = J_{tot} \times W \times h = 135 \times 10^{4}\ \frac{A}{cm^2} \times 0{,}05 \times 10^{-4}\ cm \times 0{,}05 \times 10^{-4}\ cm = 3.3750\ 10^{-5}$$

b) para $T = 400K$, $n_i = 3{,}7126 \times 10^{12}$ electrons $\cdot\ cm^{-3}$

$$p = \frac{n_i^2}{N} = 1{,}3783 \times 10^{8}\ \text{lacunas} \cdot cm^{-3}$$

$$J_{tot} = 1{,}6 \times 10^{-19}\ C \left(1350 \times \frac{cm^2}{Vs} \times 10^{17}\ cm^{-3} + 480 \frac{cm^2}{Vs} \times 1{,}3783 \times 10^{8}\ cm^{-3}\right) \times \frac{1\ V}{10^{-5}\ cm}$$

$$J_{tot} = 216 \times 10^{4}\ \frac{A}{cm^2}$$

$I = J_{tot} \times W \times h =$ 54 uA

2.11 $N_D = 3 \times 10^{16}\ cm^{-3}$

$T = 300K \rightarrow n_i = 1{,}08 \times 10^{10}$ electron cm^{-3} – Si

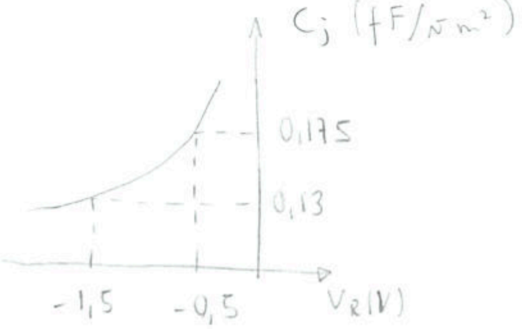
→ lado p não foi dopado, apenas lado N.

$$V_0 = \frac{kT}{q} \ln \frac{N_A N_D}{n_i^2}$$

Como lado p não foi dopado, $N_A = n_i$

$$V_0 = \frac{1{,}38 \times 10^{-23} \cdot 300}{1{,}6 \times 10^{-19}} \ln \frac{\cancel{n_i} N_D}{n_i^{\cancel{2}}} = 0{,}02587 \cdot \ln \frac{3 \times 10^{16}}{1{,}08 \times 10^{10}} = 383{,}91\ mV$$

2.13



$N_A = 10^{17}\ cm^{-3}$

$$\frac{C_{j0}}{\sqrt{1+\frac{0,5}{V_0}}} = 0,175 \quad (I)$$

$$\frac{C_{j0}}{\sqrt{1+\frac{1,5}{V_0}}} = 0,13 \quad (II)$$

$$\frac{I}{II} = \frac{1+\frac{1,5}{V_0}}{1+\frac{0,5}{V_0}} = \left(\frac{0,175}{0,13}\right)^2 \rightarrow 1+\frac{1,5}{V_0} = 1,8121 + \frac{0,9061}{V_0}$$

$$0,8121\, V_0 = 0,5939$$

$$V_0 = 0,7288\ V$$

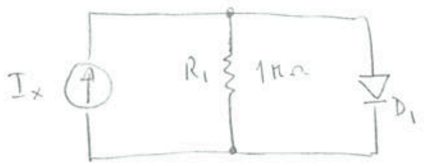
Assim, $C_{j0} = 0,175\sqrt{1+\frac{0,5}{0,7288}} = 0,2272\ fF/\mu m^2 = 0,2272\times10^{-9}\ F/cm^2$

$$C_{j0} = \sqrt{\frac{\varepsilon_{Si}\, q}{2}\,\frac{N_A N_D}{N_A+N_D}\cdot\frac{1}{V_0}} \rightarrow \frac{N_A \cdot N_D}{N_A+N_D} = (C_{j0})^2 \times \frac{2}{\varepsilon_0 \cdot q} \times V_0 = 5,3136\times10^{12}$$

$$N_D\left(1-\cancel{\frac{5,3136\times10^{12}}{N_A}}\right) = 5,3136\times10^{12} \rightarrow N_D = 5,3136\times10^{12}\ cm^{-3}$$

2.24

$I_s = 3\times10^{-16}\,A \qquad V_{D1} = ?$



$I_x = \frac{V_{D1}}{R_1} + I_{D1} = \frac{V_T}{R_1}\ln\left(\frac{I_{D1}}{I_s}\right) + I_{D1}$

Resolver por iteração!

* p/ $I_x = 1\,mA$, e supondo $V_{D1} = 0,7V$

- $V_{D1}=0,7V$, $I_{D1} = I_x - \frac{V_{D1}}{R_1} = 1m - \frac{0,7}{1K} = 0,3\,mA$

  Se $I_{D1} = 0,3\,mA \rightarrow V_{D1} = \overset{0,026}{V_T}\ln\left(\frac{0,3m}{3\times10^{-16}}\right) = 0,718\,V$

- $V_{D1} = 0,718V \rightarrow \quad I_{D1} = 1m - \frac{0,718}{1K} = 0,282\,mA$

  $V_{D1} = 26mV\times\ln\left(\frac{0,282m}{3\times10^{-16}}\right) = 0,717V$

* p/ $I_x = 2\,mA$

- $V_{D1} = 0,717V$, $I_{D1} = 2m - \frac{0,717}{1K} = 1,282\,mA$

  $V_{D1} = 26mV\,\ln\left(\frac{1,282m}{3\times10^{-16}}\right) = 0,756\,V$

- $V_{D1} = 0,756$, $I_{D1} = 2m - \frac{0,756}{1K} = 1,24\,mA$

  $V_{D1} = 26mV\,\ln\left(\frac{1,24m}{3\times10^{-16}}\right) = 0,755\,V$

* p/ $I_x = 4\,mA$

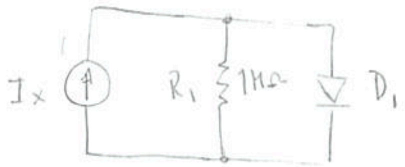
- $V_{D1} = 0,755V$, $I_{D1} = 4m - \frac{0,755}{1K} = 3,245\,mA$

  $V_{D1} = 26m\,\ln\left(\frac{3,245m}{3\times10^{-16}}\right) = 0,78\,V$

- $V_{D1} = 0,78V$, $I_{D1} = 4m - \frac{0,78}{1K} = 3,22\,mA$

  $V_{D1} = 26m\,\ln\left(\frac{3,22m}{3\times10^{-16}}\right) = 0,78V$

2.25



$I_{D1} = 0{,}5\,mA$

$I_x = 1{,}3\,mA$

$I_s = ?$

$$I_x = I_{R1} + I_{D1} \rightarrow I_{R1} = 0{,}8\,mA \rightarrow V_{R1} = I_{R1} \cdot R_1 = 0{,}8V$$

$$V_{R1} = V_{D1} = 0{,}8V$$

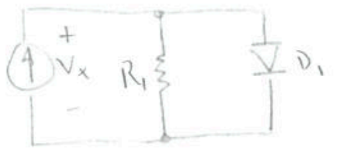
$$I_s = I_{D1}\, \exp\left(-\frac{V_{D1}}{V_T}\right) = 0{,}5m\ \exp\left(\frac{0{,}8}{26m}\right) = 2{,}17 \times 10^{-17}\,A$$

2.27

Determinar R_1 e I_s

$\rightarrow I_x = 1mA \rightarrow V_x = 1{,}2V$

$\rightarrow I_x = 2mA \rightarrow V_x = 1{,}8V$



$$I_{D1} = I_x - \frac{V_x}{R_1}$$

$$V_x = V_T\ \ln\left(\frac{I_{D1}}{I_s}\right) = V_T\ \ln\left(\frac{I_x - \frac{V_x}{R_1}}{I_s}\right)$$

p/ $I_x = 1mA$ e $V_x = 1{,}2V$

$$1{,}2V = 26m\ \ln\left(\frac{1m - \frac{1{,}2}{R_1}}{I_s}\right) \quad \text{eq. 1}$$

p/ $I_x = 2mA$ e $V_x = 1{,}8V$

$$1{,}8V = 26m\ \ln\left(\frac{2m - \frac{1{,}8}{R_1}}{I_s}\right) \quad \text{eq. 2}$$

$$\text{eq 2} - \text{eq 1} \Rightarrow \quad 0{,}6V = 26m\ \ln\left(\frac{2m - \frac{1{,}8}{R_1}}{1m - \frac{1{,}2}{R_1}}\right) \rightarrow \frac{2m - \frac{1{,}8}{R_1}}{1m - \frac{1{,}2}{R_1}} = e^{0{,}6/26m}$$

$$R_1 = \frac{1{,}2\ e^{0{,}6/26m} - 1{,}8}{1m \cdot e^{0{,}6/26m} - 2mA} = 1200\,\Omega$$

$$I_s = I_{D1}\, \exp\left(-\frac{V_x}{V_T}\right) = \left(2mA - \frac{1{,}8}{1{,}2k}\right) \exp\left(-\frac{1{,}8}{26m}\right)$$

$$I_s = 4{,}29 \times 10^{-34}\,A$$