ECE/UCONN **QUIZ#1** ECE 4211 **Open book/Notes** 03/02/2017 F. Jain Name Solution Set

3 questions 40 points. Q.1 [18 point], Q.2 (16), Q.3 (6 point); Bonus Question 2 points

Q.1. Figure 1 shows an n^+-p Si diode.

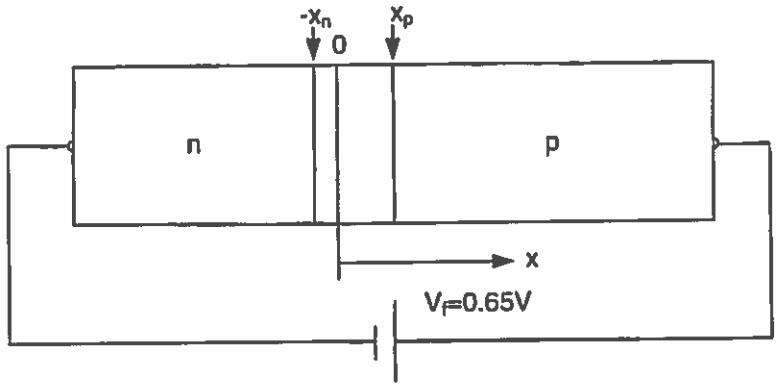


Fig. 1 An abrupt n-p Si diode under forward bias. The junction widths are $-x_{n0}$ and x_{p0} under equilibrium.

n^+-side: Donor concentration $N_D=10^{18}$ cm^{-3}, minority hole lifetime $\tau_p=2\times10^{-6}$ sec. Minority hole diffusion coefficient $D_p=12.5$ cm^2/sec.

p-side: Acceptor concentration $N_A=10^{16}$ cm^{-3}, $\tau_n=10^{-5}$ sec. $D_n=40$ cm^2/sec.

Effective mass: electrons $m_c=m_n=0.26m_o$, holes $m_h=m_p=0.64\ m_o$,

Junction area $A=10^{-3}$ cm^{-2}, n_i (300K) $=1.5\times10^{10}$ cm^{-3}. ε_r(Si)=11.8, $\varepsilon_0=8.85\times10^{-14}$ F/cm, $\varepsilon_s=\varepsilon_r\varepsilon_0$. Assume all donors and acceptors are ionized at T=300 K. E_g = 1.1eV, Boltzmann Constant k= 8.65×10^{-5} eV/K.

Do ~~any four parts out of (a) to (e)~~

4 (a) Calculate the built-in voltage V_{bi} at 300K.

V_{bi}

$$V_{bi} = \frac{KT}{q}\ln\left(\frac{N_A N_D}{n_i^2}\right) = 0.0259\ln\left(\frac{10^{16}\times10^{18}}{2.25\times10^{20}}\right) = 0.0259\ln\left(\frac{10^{14}}{2.25}\right) = 0.8139\,V$$

$n_i = 1.5\times10^{10}\ cm^{-3}$

$KT = 0.0259\ V$

(b) Compute the junction width at zero bias (equilibrium) and compare it with the value W = 3.26×10^{-5}cm at 300°K.

5 W=

$N_D = 10^{18}$, $N_A = 10^{16}$

$N_A + N_D \simeq N_D$

$$W_0 = \left[\frac{2V_{bi}\,\varepsilon_r\,\varepsilon_0\,(N_A+N_D)}{q\,N_A N_D}\right]^{1/2}$$

$$\frac{N_A+N_D}{N_A N_D} \simeq \frac{N_D}{N_A N_D} \simeq$$

$$\simeq \left[\frac{2V_{bi}\,\varepsilon_r\,\varepsilon_0}{q\,N_A}\right]^{1/2}$$

$$= \left[\frac{2\times0.8139\times11.8\times8.854\times10^{-14}}{1.6\times10^{-19}\times10^{16}}\right]^{1/2} = \left[\frac{2\times0.8139\times11.8\times8.85}{1.6\times10^{3}}\right]$$

$$= \left(1.0629\times10^{-9}\right)^{1/2} = 3.26\times10^{-5}\ cm$$

(c) Given the expressions of electron current $I_n(x)$ in p-region outside of junction ($x > x_p$) and hole current $I_p(x)$ in the n-region ($x < -x_n$) as,

$$I_n(x) = A J_n(x) = -\frac{q A D_n n_{pn}}{L_n} e^{-\frac{(x-x_p)}{L_n}} * \left(e^{\frac{qV_f}{kT}} - 1 \right) \quad (78A)$$

$$I_p(x) = A J_p(x) = -\frac{q A D_p p_{no}}{L_p} e^{-\frac{(x-x_n)}{L_p}} * \left(e^{\frac{qV_f}{kT}} - 1 \right) \quad (79A)$$

Compute the electron current at the junction $I_n(x=x_p)$ **and hole current** $I_p(x=-x_n)$ **at a forward bias of 0.65V.**

Electron current $I_n(x=x_p)$

5

$$I_n = \frac{q A D_n n_{p0}}{L_n} \left(e^{\frac{qV_f}{kT}} - 1 \right).$$

$$\cong \frac{1.6\times10^{-19}\times10^{-3}\times40\times2.25\times10^{4}}{2\times10^{-2}} \cdot e^{\frac{0.65}{0.0259}}$$

$$= 7.2\times10^{-15} * 7.93\times10^{10}$$

$$= \boxed{5.709\times10^{-4} = 0.5709\,mA}$$

$D_n = 40\ cm^2/s$, $A = 10^{-3}$

1 $L_n = \sqrt{D_n \tau_n} = \sqrt{40\times10^{-5}}$ $2\times$

1 $n_{p0} = \frac{n_i^2}{N_A} = \frac{n_i^2}{N_A} = \frac{2.25\times10^{20}}{10^{16}}$

$n_{p0} = 2.25\times10$

$e^{\frac{qV_f}{kT}} - 1 \simeq e^{\frac{qV_f}{kT}}$

1 $1 \ll 7.93\times10^{10}$ $= e^{0.65/0.025}$

$= 7.93\times10^{10}$

Hole current $I_p(x=-x_n)$.

$$I_p = \frac{q A D_p p_{n0}}{L_p} \left(e^{\frac{qV_f}{kT}} - 1 \right);$$

4

$$= \frac{1.6\times10^{-19}\times10^{-3}\times12.5\times2.25\times10^{2}}{5\times10^{-3}} \left(7.93\times10^{10} \right)$$

$$= \frac{1.6\times12.5\times2.25}{5} * 10^{-17} * 7.93\times10^{10}$$

1 $= 71.37\times10^{-7} = \boxed{7.137\times10^{-6}\,A}$

$D_p = 12.5\ cm^2/sec$ $A = 10^{-3}$

1 $L_p = \sqrt{D_p \tau_p} = \sqrt{12.5\times2\times10^{-6}} = 5\times10^{-3}\,cm$

1 $p_{n0} = \frac{n_i^2}{N_D} = \frac{2.25\times10^{20}}{10^{18}} = 2.25\times10^{2}\ cm^{-3}$

Q. 2 Fig. 2 shows an n-p-n transistor which is a reconfiguration of n-p junction of Fig. 1 where an n-type collector is added.

The emitter base junction is forward biased $V_f = V_{BE} = 0.65$ Volts. The p-type **base width W = 10.0 microns = 10 x10^{-4} cm**. Other parameters are given below.

Emitter n$^+$-side: Donor concentration $N_D=10^{18}$ cm^{-3}, minority hole lifetime $\tau_{pE}=2\times10^{-6}$ sec.
Minority hole diffusion coefficient $D_{p,E}=12.5$ cm^2/sec.

Base **p-side**: Acceptor concentration $N_{A,B}=1\times10^{16}$ cm^{-3}, $\tau_{nB}=10^{-5}$ sec. $D_{n,B}=40$ cm^2/sec
Effective mass: electrons $m_e=m_n=0.26m_o$, holes $m_h=m_p=0.64\ m_o$,
Junction area base-emitter $A_{BE}=10^{-3}$ cm^{-2},
Base-collector area $A_{BC} = 1\times10^{-3}$ cm^{-2}.

Collector n-side: $N_{D,Collector} = 10^{15}$ cm^{-3}, minority hole lifetime $\tau_{pC}=2\times10^{-6}$ sec.
Minority hole diffusion coefficient $D_{p,C}=15$ cm^2/sec.
n_i (300K)$=1.5\times10^{10}$ cm^{-3}. ε_r(Si)=11.8, $\varepsilon_0=8.85\times10^{-14}$ F/cm, $\varepsilon_s=\varepsilon_r\varepsilon_0$.

Given: $$I_{EN}(x) = qA_{BE}D_{n,B}\left[-\frac{n_{po,B}}{L_n}\frac{\cosh(x/L_n)}{\sinh(W/L_n)} + \frac{n_{po,B}}{\sinh(W/L_n)}\left(e^{\frac{qV_{BE}}{kT}}-1\right)\left(-\frac{1}{L_n}\right)\cosh\left(\frac{W-x}{L_n}\right)\right]$$

$$I_{EN}(x=0) = \frac{qA_{BE}D_{n,B}n_{po,B}}{L_n}\left[\frac{1}{\sinh(W/L_n)} + \frac{-1}{\sinh(W/L_n)}\left(e^{\frac{qV_{BE}}{kT}}-1\right)\cosh\left(\frac{W}{L_n}\right)\right],$$

Neglecting first term,

$$I_{EN}(x=0) = -\frac{qA_{BE}D_{n,B}n_{po,B}}{L_n}\left[\left(e^{\frac{qV_{BE}}{kT}}-1\right)\coth\left(\frac{W}{L_n}\right)\right],\ \coth\left(\frac{W}{L_n}\right) \cong \frac{L_n}{W} \quad \text{if } W << L_n$$

(a) Compute the electron current I_{En} at x=0 at the base boundary of n-p emitter base junction.

$D_{n,B} = 40\ cm^2/s$

$L_{n,B} = \sqrt{40\times10^{-5}} = 2\times10^{-2}$ cm

$n_{po,B} = \frac{2.25\times10^{20}}{10^{16}} = 2.25\times10^{4}\ cm^{-3}$

$$I_{EN}(x=0) = -\frac{1.6\times10^{-19}\times1\times10^{-3}\times40\times2.25\times10^{4}}{2\times10^{-2}}\frac{L_n}{W}\left(e^{\frac{qV_{EB}}{kT}}-1\right)$$

$$= -\frac{1.6\times10^{-19}\times10^{-3}\times40\times2.25\times10^{4}}{10\times10^{-4}}(7.93\times10^{10})$$

$$= \frac{1.6\times40\times2.25\times10^{-19}\times10^{1}}{10^{-3}}\times7.93\times10^{10}$$

$$= 1.1419\times10^{3}\times10^{-05}$$

$$= 1.1419\times10^{-2} = 11.419\ mA$$

(b) The hole current I_{EP} in the n-p-n BJT of fig. 2 is same as in n-p diode of Fig. 1. **Circle one.**

True **False**

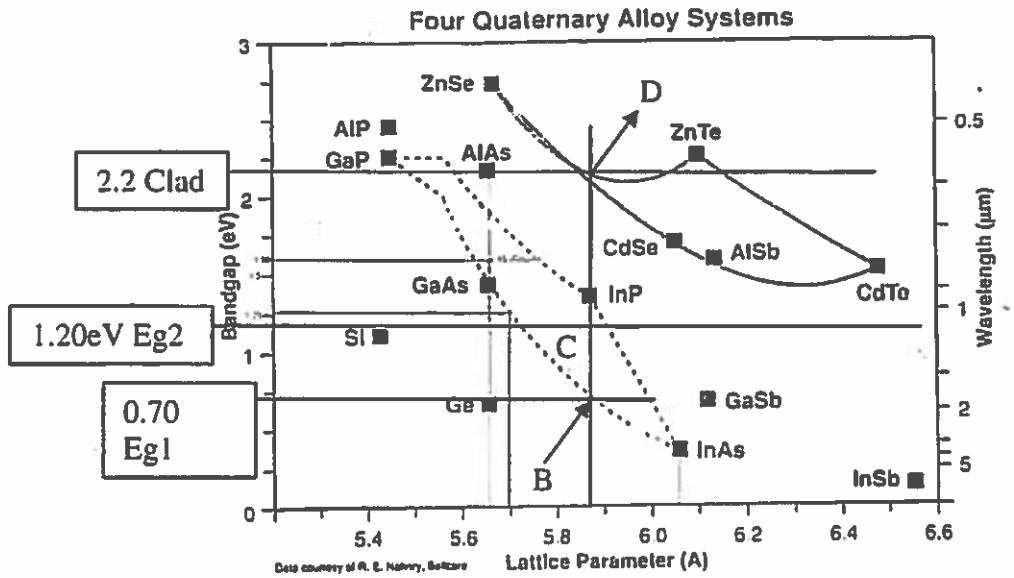
(c) Does the injection efficiency $\gamma = [\frac{I_{EN}}{I_{EP}+I_{EN}}]$ of the emitter-base junction in the BJT depend of base width W. **Circle one.**

YES **NO .**

Q.3. (a) Find the composition of point C (Fig. 3 below) at the intersection of 1.2eV (Eg2) horizontal line and InP – B vertical line.
Given the composition of point ~~A~~ B (energy gap Eg1=0.7eV) is $In_{0.53}Ga_{0.47}As$ and InP energy gap is 1.34eV.

Lattice Parameter and Bandgap Data

3



$B = In_{0.53}Ga_{0.47}As$ (Given)

Point C: P $\Rightarrow \frac{BC}{B\text{-}InP} = \frac{1.2-0.7}{1.34-0.7} = \frac{0.5}{0.64} = 0.78$

$As = 1-0.78 = 0.22$

$In_{0.896}Ga_{0.104}As_{0.22}P_{0.78}$

$Ga = 1 - In = 1-0.896 = 0.104$ $\quad In = 0.53 + 0.47\left(\frac{0.5}{0.64}\right) = 0.53 + 0.47\times 0.78 = 0.8966$

3 (b) What are the ΔE_c and ΔE_v values for the single or double heterostructure N-p-P light emitting diode using $In_{0.53}Ga_{0.47}As$ as the lower energy gap active layer and InGaAsP ($1.2eV=E_{g2}$) as the higher energy gap layer for N or P layers. Use ΔE_c to be 0.6 of band gap difference.

$E_g(c) - E_g(B) = 1.2 - 0.7 = 0.5 = \Delta E_g$ 1.

$\Delta E_c + \Delta E_v = \Delta E_g$

$\Rightarrow \Delta E_c = 0.6 \times 0.5 = 0.3$ eV

$\Rightarrow \Delta E_v = 0.4 \times 0.5 = 0.2$

Bonus Question: 2 points
Modify the figure below for N-AlGaAs/pGaAs/P-AlGaAs heterodiode to show the N-p-P diode using $In_{0.53}Ga_{0.47}As$ as the active layer and 1.2eV InGaAsP as the wider energy gap N and P layers.