NANYANG TECHNOLOGICAL UNIVERSITY
SCHOOL OF ELECTRICAL & ELECTRONIC ENGINEERING
ACADEMIC YEAR 2022-2023
SEMESTER 1

EE3013 SEMINCONDUCTOR DEVICES AND PROCESSING

Recap of PN Junctions

1. An abrupt junction silicon p-n diode has a p-layer acceptor doping density of 10^{18} cm^{-3} and n-side donor doping density of 10^{15} cm^{-3}. Assume that the dopants are fully ionized. For this junction in equilibrium at 300 K:

(a) Compute the position of the Fermi level (with respect to the conduction band edge) on both sides of the junction.

(b) Sketch the band diagram (with the energy axis drawn to scale) and estimate the built-in potential.

(c) Computer V_{bi} directly from the doping densities and the intrinsic concentration, and compare the result with that from part b).

(d) Calculate the widths of the depletion regions on either side of the junction.

(e) Calculate the maximum electric field in the depletion region.

Solution:

(a) For n- and p-type Si:

$$n = N_C \exp\left(\frac{E_F - E_C}{kT}\right) = N_D$$

$$p = N_V \exp\left(\frac{E_V - E_F}{kT}\right) = N_A$$

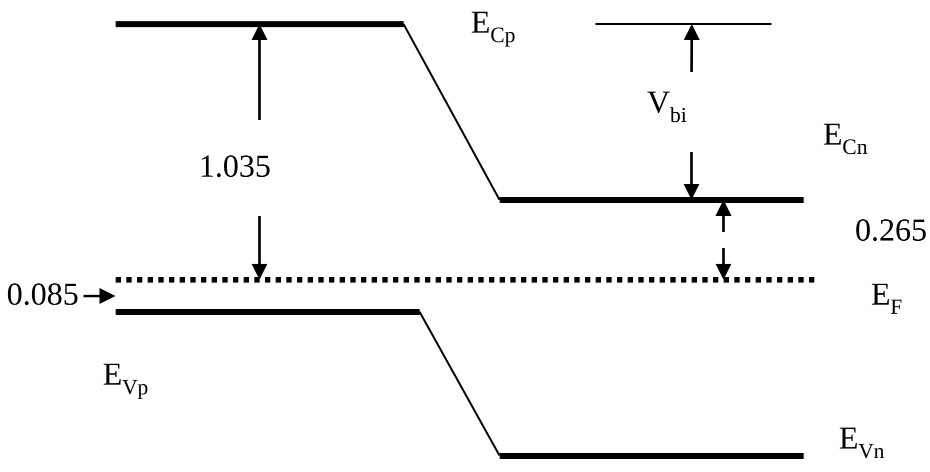
we obtain

$$E_F - E_C\Big|_n = 0.0259 \ln\left(\frac{10^{15}}{2.8\times10^{19}}\right) = -0.265 eV$$

$$E_V - E_F\Big|_p = 0.0259 \ln\left(\frac{10^{18}}{2.66\times10^{19}}\right) = -0.085 eV$$

$$E_C - E_F\Big|_p = 1.12 - 0.085 = 1.035 eV$$

(b) Draw E_F horizontally through the device, then add E_{Vp} and E_{Cn}; finally draw E_{Cp} and E_{Vn} using E_g = 1.12 eV.



(c) $$V_{bi} = \frac{kT}{q} \ln \frac{N_A N_D}{n_i^2} = 0.0259 \ln \frac{10^{33}}{\left(9.65 \times 10^9\right)^2} = 0.776 eV$$

From the diagram above: V_{bi} = 1.035 – 0.265 = 0.77 eV

(d)

$$W = \sqrt{\frac{2\varepsilon_s}{q}\left(V_{bi} - V\right)\left(\frac{N_A + N_D}{N_D N_A}\right)} \quad x_p = 9.99 \times 1010 m = 9.99 \times 10^{-4} \mu m$$

$$x_n = 0.999 \mu m$$

V =0, ε_s = 11.9 x 8.85 x 10 $^{-14}$ F cm^{-1}, W = 1μm

$$x_n = \frac{N_A W}{N_A + N_D}, x_p = \frac{N_D W}{N_A + N_D}$$

➔ X_p = 9.99x10^{-4} μm

➔ X_n = 0.999 μm

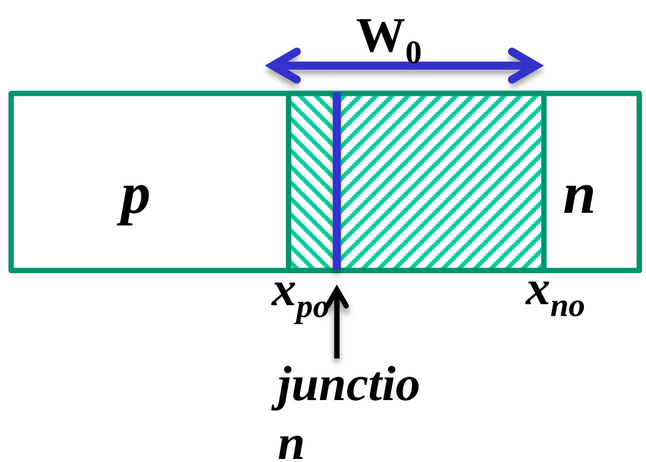
(e)

$$\xi_{\max} = \xi_{x=0} = -\frac{qN_A x_p}{\varepsilon_s} = -1.52 \times 10^4 V cm^{-1}$$

2. Consider a uniformly doped abrupt pn junction at 300 K. At thermal equilibrium, it is designed such that 10 % of the total depletion width region lies in the p region. You are given that the built in potential is 0.8 V. Determine the doping concentration N_a and N_d of the p and n region, respectively, and the total depletion width.

(Hint: Consider charge neutrality and $x_{n0} + x_{p0} = W$ to relate N_a and N_d. You can relate N_a and N_d via the expression for V_{bi}. Then, solve the two equations.)

[2.59×10^{16} cm^{-3}; 2.33×10^{17} cm^{-3}; 0.212 μm]



6

Solution 2

The desired built-in voltage is 0.8 V. Thus,

$$V_{\mathrm{bi}} = \frac{k_{\mathrm{B}}T}{q}\ln\left(\frac{N_{\mathrm{a}}N_{\mathrm{d}}}{n_{\mathrm{i}}^2}\right) = 0.8\ \mathrm{V} \qquad (1)$$

The second requirement is that 10 % of the total depletion widt
is to be in the p region, i.e.

$$\frac{x_{\mathrm{p0}}}{x_{\mathrm{p0}} + x_{\mathrm{n0}}} = 0.1 \Rightarrow x_{\mathrm{n0}} = 9x_{\mathrm{p0}} \qquad (2)$$

In addition,

$$x_{\mathrm{p0}}N_{\mathrm{a}} = x_{\mathrm{n0}}N_{\mathrm{d}} \Rightarrow N_{\mathrm{a}} = 9N_{\mathrm{d}} \qquad (3)$$

$$V_o = \frac{kT}{q}\ln\left(\frac{N_a N_d}{n_i^2}\right)$$

$$\Rightarrow qV_o / kT = \ln\left(\frac{9N_d^{\ 2}}{n_i^{\ 2}}\right) = 2\ln\left(\frac{3N_d}{n_i}\right)$$

$$\Rightarrow \left(\frac{3N_d}{n_i}\right) = \exp(qV_o / 2kT)$$

$$\Rightarrow N_d = \frac{n_i}{3}\exp(qV_o / 2kT)$$

$$N_{\mathrm{d}} = \frac{n_{\mathrm{i}}}{3}\exp\left(\frac{q}{2k_{\mathrm{B}}T}V_{\mathrm{bi}}\right)$$

$$= \frac{1.5\times10^{10}}{3}\exp\left(\frac{1.6\times10^{-19}\times0.8}{2\times1.38\times10^{-23}\times300}\right)$$

$$= 2.59\times10^{16}\ \mathrm{cm}^{-3}$$

$$N_{\mathrm{a}} = 9N_{\mathrm{d}} = 2.33\times10^{17}\ \mathrm{cm}^{-3}$$

Solution 2 (continued)

Total depletion width,

$$W = \left[\frac{2\varepsilon_r \varepsilon_0}{q} V_{bi} \left(\frac{1}{N_a} + \frac{1}{N_d} \right) \right]^{1/2}$$

$$= \left[\frac{2 \times 11.8 \times 8.85 \times 10^{-14} \times 0.8}{1.6 \times 10^{-19}} \times \left(\frac{1}{2.33 \times 10^{17}} + \frac{1}{2.59 \times 10^{16}} \right) \right]^{1/2}$$

$$= 2.12 \times 10^{-5} \text{ cm} \quad \text{or } 0.212\ \mu\text{m}$$

3. Assume that the p-n abrupt junction has $N_A = 10^{17}$ cm^{-3} and $N_D = 10^{15}$ cm^{-3},

a) Calculate V_{bi} at 250 and 500 K and list V_{bi} versus *T*.

b) Comment on your result in terms of energy band diagram.

c) Find the depletion layer width and maximum field at zero bias for $T = 500$ K.

Assume that the intrinsic carrier concentrations at 250 and 500 K are 1.5×10^{8} cm^{-3} and 2.2×10^{14} cm^{-3} respectively.

(a) From the figure, the intrinsic carrier concentrations at different temperatures can be obtained, one can thus get built-in potential.

$$V_{bi} = \frac{kT}{q}\ln\left(\frac{N_A N_D}{n_i^2}\right) = \frac{1.38\times10^{-23}T}{1.6\times10^{-19}}\ln\left(\frac{10^{17}\times10^{15}}{n_i^2}\right)$$

$$= 8.63\times10^{-5}\times T\times\ln\left(\frac{10^{32}}{n_i^2}\right)$$

The V_{bi} results are listed in the following table.

T	n_i	V_{bi} (V)
250	1.500E+08	0.777
500	2.20E+14	0.329

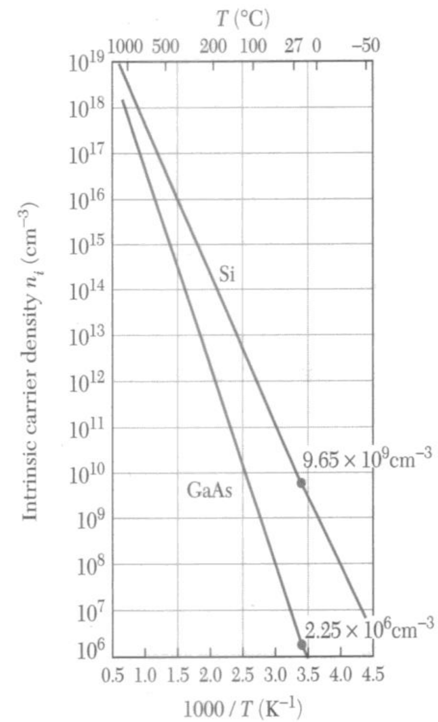


Fig. 22 Intrinsic carrier densities in Si and GaAs as a function of the reciprocal of temperature.[5–7]

(b) $E_g(300k) = 1.12eV$; $E_g(500k) = 1.05eV$ => n_i and p_i increase

Thus, V_{bi} is decreased as the temperature is increased.

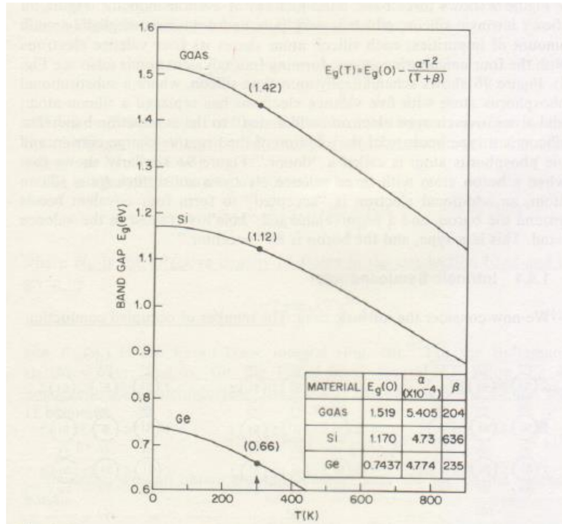


Fig. 8 Energy bandgaps of Ge, Si, and GaAs as a function of temperature. (After Thurmond, Ref. 20.)

(C) Depletion width W and maximum field at zero bias at T=500 K

$$W = \sqrt{\frac{2\varepsilon_s V_{bi}}{qN_D}} = 0.658\,\mu m$$

$$\xi_{\max} = \frac{qN_D W}{\varepsilon_s} = 1\times 10^4 V/cm$$

4. A one-sided p-n junction at 300 K is doped with $N_A = 10^{19}$ cm^{-3}. Design the junction so that $C_j = 0.85 \times 10^{-8}$ F/cm^2 at a reverse voltage of 4 V.

We know

$$\frac{1}{{C_j}^2} = \frac{2(V_{bi} - V)}{q\varepsilon_s N_B} \Rightarrow N_D = \frac{2(V_{bi} - V_R)}{q\varepsilon_s} {C_j}^2$$

$$\because V_R >> V_{bi} \Rightarrow N_D \cong \frac{2(V_R)}{q\varepsilon_s} {C_j}^2$$

$$= \frac{2 \times 4}{1.6 \times 10^{-19} \times 11.9 \times 8.85 \times 10^{-14}} \times (0.85 \times 10^{-8})^2$$

$$\Rightarrow N_d = 3.43 \times 10^{15} \, \text{cm}^{-3}$$

We can select the n-type doping concentration of 3.43×10^{15}cm^{-3}.

If you do not neglect V_{bi}, and use the equation $V_{bi} = \frac{kT}{q} \ln \frac{N_A N_D}{n_i^2}$

Then the above equation for $1/C_j^2$ becomes

$$N_D = \frac{2C_j^2}{q\varepsilon_s}\left[\frac{kT}{q}\left\{\ln \frac{N_A}{n_i^2} + \ln N_D\right\} - V_R\right]$$

$N_D = 3.38\text{x}10^{15} + 2.22\text{x}10^{13} \ln(N_D)$

Solve using iteration. The solution converges. Two iterations are sufficient. Take an initial value of

$N_D = 1\text{x } 10^{15}$ cm^{-3} ($\ll N_A$)

Final result: $N_D = 4.18 \text{ x } 10^{15}$ cm^{-3}

5. Design the Si p-n diode such that $J_n = 25$ A.cm^{-2} and $J_p = 7$ A.cm^{-2} at $V_a = 0.7$ V. Other parameters include $n_i = 9.65 \times 10^9$ cm^{-3}, $D_n = 21$ cm^2/s, $D_p = 10$ cm^2/s and $\tau_n = \tau_p = 5 \times 10^{-7}$ s. Assume that J_p and J_n are given by expressions of the form $(qD_p p_{no}/L_p).(e^{qV/kT} - 1)$ and $(qD_n n_{po}/L_n).(e^{qV/kT} - 1)$ respectively.

$$J_p\left(x_n\right) = \frac{qD_p p_{no}}{L_p}\left(e^{qV/kT} - 1\right) = q\sqrt{\frac{D_p}{\tau_{po}}} \times \frac{n_i^{\ 2}}{N_D} \times \left[e^{\left(\frac{qV_a}{kT}\right)} - 1\right]$$

$$7 = 1.6 \times 10^{-19} \times \sqrt{\frac{10}{5 \times 10^{-7}}} \times \frac{\left(9.65 \times 10^9\right)^2}{N_D} \times \left[e^{\left(\frac{0.7}{0.0259}\right)} - 1\right]$$

$$\therefore N_D = 5.2 \times 10^{15}\,\mathrm{cm}^{-3}$$

$$J_n\left(-x_p\right) = \frac{qD_n n_{po}}{L_n}\left(e^{qV/kT}-1\right) = q\sqrt{\frac{D_n}{\tau_{no}}} \times \frac{n_i^{\ 2}}{N_A} \times \left[e^{\left(\frac{qV_a}{kT}\right)} - 1\right]$$

$$25 = 1.6\times10^{-19} \times \sqrt{\frac{21}{5\times10^{-7}}} \times \frac{\left(9.65\times10^{9}\right)^2}{N_A} \times \left[e^{\left(\frac{0.7}{0.0259}\right)} - 1\right]$$

$$\therefore N_A = 2.1\times10^{15}\,\text{cm}^{-3}$$