Solutions EEE105 2009-10

Question 1

(a) For a metal (conductor) there is no band-gap between conduction and valence states meaning there is no thermal barrier to conduction. For an insulator however, there is a band-gap which is so large in comparison to the thermal energy of the electrons that there essentially are no free carriers at room temperature.

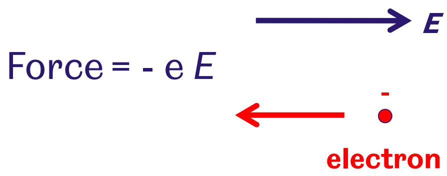
(b)

i) If there is a non-uniform carrier concentration, there will be diffusion of the carriers. This is governed by Fick's law.

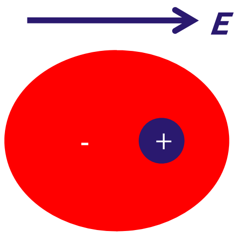
$$\varphi_e(x) = -D_e \frac{dn}{dx} \qquad J_e = qD_e \frac{dn}{dx}$$

The flux density of particles is governed by a constant of proportionality and the rate of change of concentration. Current density is this flux multiplied by the electron charge.

ii) If an electric field is applied a force is experienced by the electron, which will accelerate in the opposite direction to the E-field, leading to a drift current.



iii) For an insulator the electrons are not free to move around the crystal. The electric field may move the electron cloud around the atom with the effect of realizing an electric polarization.



(c)

i) Average scattering time.

$$\tau = \frac{\mu m^*}{q}$$

$$\tau = \frac{0.12 \text{ x } 0.98 \text{ x } 9.11\text{x}10^{-31}}{1.6 \text{ x } 10^{-19}} = 6.7\text{x}10^{-13}\text{s}$$

ii) Drift Velocity

$$v_d = -\mu E = -\mu \frac{V}{L} = -0.12 \frac{10}{0.01} = -120 \text{ ms}^{-1}$$

iii) Electron concentration.

$$R = \frac{V}{I} = \frac{10}{2\text{x}10^{-3}} = 5\text{x}10^{3}\,\Omega$$

$$R = \frac{L}{\sigma A} \qquad \sigma = \frac{L}{RA} = \frac{0.01}{5\text{x}10^{3} \text{ x } 2\text{x}10^{-6}} = 1 \ \Omega^{-1}\text{m}^{-1}$$

$$n = \frac{\sigma}{q\mu} = \frac{1}{1.6\text{x}10^{-19} \text{ x } 0.12} = 5.2\text{x}10^{19} \ \ \text{m}^{-3}$$

Question 2

a) The free carriers in an intrinsic semiconductor are due to thermal generation.

b) In any material there will be carriers being generated and recombining all the time. In equilibrium the rate of generation and recombination will be equal and hence there will be a constant number of free carriers in the material. The generation rate is a constant, independent of doping which only depends on the temperature of the material.

Considering a free electron the probability of it recombining with a hole will be dependent on the density of holes in the material. Thus the rate of recombination will be proportional to the density of holes in the material, p. By similar analogy the rate of recombination will also be proportional to the density of electrons in a material, n.

Thus we can say in thermal equilibrium that:

$$G = R = Bnp = Bn_i p_i = Bn_i^2$$

in an intrinsic material, where B is a constant of proportionality.

The doped material is n-type, therefore the majority carriers are electrons and their density is given by the density of dopants (assuming $n >> n_i$). Knowing that the generation rate remains the same we can write:

$$G = Bn_i^2 = Bnp_n$$

and hence

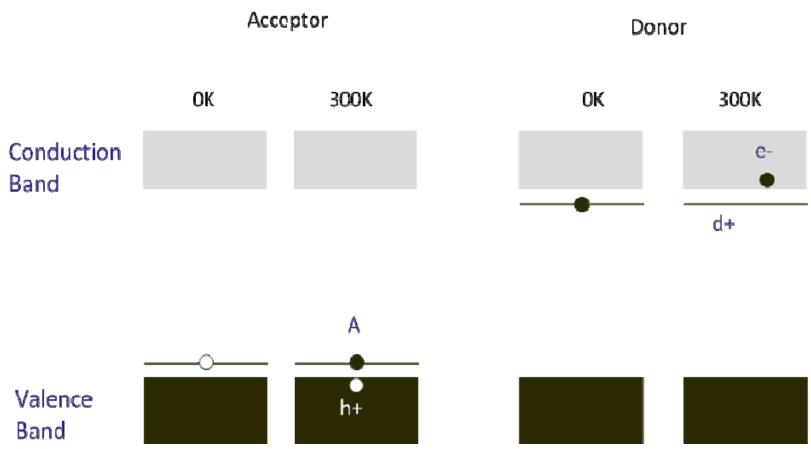
$$p_n = {n_i^2}/{n}$$

c)

i) Choice of dopants – this is dictated by the valency of the dopant atom. For Si (group 4), acceptors, which introduce free holes, have a valency of 3. Donor, which introduce free electrons have a valency of 5.

ii) Number of dopants. This is generally a small fraction of the number density (e.g. 1 in 1000000 to 1 in 1000). A larger number density tends to result in the material being described as an alloy semiconductor rather than a doped semiconductor.

iii)



d)

$$C = n_i T^{-3/2} \exp\left(\frac{W_g}{2kT}\right)$$

Now W_g = 1.12 eV = 1.79×10^{-19} J

Assuming room temperature is 293K gives

$C = 1.19 \times 10^{22}$ m^{-3}K$^{-3/2}$

Substituting in the equation given for T=350 K gives

$n_i = 6.98 \times 10^{17}$ m^{-3}

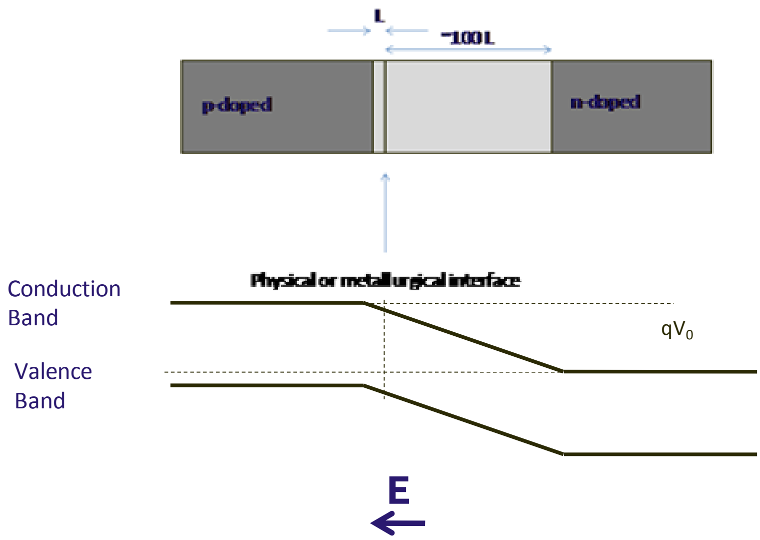
Question 3

i) When a piece of p-type material is brought together with a piece of n-type semiconductor then there will be a concentration gradient of electrons and holes in the junction region. As a result electrons will diffuse into the p-type material and holes into the n-type material, where they will recombine with the majority carriers. However, as the electrons and holes diffuse they will leave behind their donor and acceptor atoms, which are ionised. These atoms cannot move as they are bonded into the crystal. As the diffusion progresses so the number of exposed donors and acceptors increase. This causes an increasing electric field in the junction region which acts to oppose further electron and hole diffusion. Eventually the field is sufficiently strong to set up a drift current that exactly opposes the diffusion current of electrons and holes and the diode reaches equilibrium. The depletion region is the region where all the electrons and holes have diffused and recombined, leaving only their exposed donor and acceptors behind. The layer acts like an insulator as all the free charge carriers have recombined away.

ii) $$W = \left(\frac{2\varepsilon_0 \varepsilon_r (V_0 - V_f)}{q} \left(\frac{N_a + N_d}{N_a N_d} \right) \right)^{0.5} = \left(\frac{2x8.85x10^{-12} x12x(0.7+1)}{1.6x10^{-19}} \left(\frac{1x10^{25} + 1x10^{23}}{1x10^{23} x1x10^{25}} \right) \right)^{0.5}$$

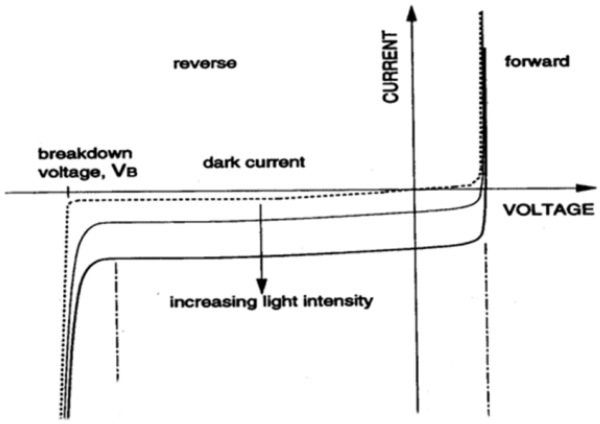
$$W = 1.51x10^{-7} m = 0.151 \mu m = 151 nm$$

iii)



iv)

1) 800nm



Breakdown may be Zener or Avalanche.

2) 1550nm the light is not of sufficient energy to promote electrons to the conduction band. The I-V characteristics are the same as in the dark at all powers.

Question 4

a) A BJT consists of strongly asymmetric doping profiles to give a p+-n or n+-p junction which acts as the "emitter" of one type of charge carrier (holes and electrons, respectively). The emitter efficiency is the ratio of current due to the desired charge carrier to the total current at the emitter-base junction. The base transport factor is the ratio of carriers collected in the collector to the injected / emitted charge carriers.

b) The asymmetric doping of the emitter-base junction of the BJT acts to ensure current is mainly due to just one carrier. This ensures the emitter efficiency is high.

The thickness of the base must be very small compared to the minority carrier diffusion length so as to minimize recombination in the base of the injected / emitted minority carriers.

$$W_B << L_h = (D_h \tau_h)^{1/2}$$

c) Emitter efficiency $\gamma = \dfrac{i_{Eh}}{i_{Ee} + i_{Eh}}$

Base transport factor, B, $I_C = BI_{Eh}$

Base current - $i_B = i_{Ee} + i_{Bh} = i_{Be} + (1 - B)i_{Ep}$

$$\frac{i_C}{i_B} = \frac{Bi_{Eh}}{i_{Ee} + (1 - B)i_{Eh}}$$

Assuming $\left(i_{Ee} / i_{Ee} + i_{Eh}\right) \sim 0$

$$\frac{i_C}{i_B} = \frac{B\left[i_{Eh} / i_{Ee} + i_{Eh}\right]}{1 - B\left[i_{Eh} / i_{Ee} + i_{Eh}\right]} = \frac{B\gamma}{1 - B\gamma} = \frac{\alpha}{1 - \alpha} \equiv \beta$$

Where β is the current amplification factor.

d).

From inspection of saturation current equation.

$$J_e = \frac{qL_e n_p}{\tau_e}$$

$$J_h = \frac{qL_h p_n}{\tau_h}$$

Minority carrier lifetimes in base and emitter are known. The minority carrier diffusion length can be

calculated knowing

$L = \sqrt{D\tau}$ and $D = \frac{kT}{q}\mu$

as the electron and hole mobilities are given in the materials info on the first page. The minority carrier density must be calculated

$$\mathrm{G = Bn^2_i = R = B\,n\,p}$$

So $\mathrm{n_p} = \frac{\mathrm{n^2_i}}{\mathrm{p_p}}$ and $\mathrm{p_n} = \frac{\mathrm{n^2_i}}{\mathrm{n_n}}$

Putting this all together

$$\frac{J_e}{J_h} = \frac{qL_e n_p}{\tau_e}\frac{\tau_h}{qL_h p_n} = \frac{\tau_h}{\tau_e}\frac{L_e}{L_h}\frac{n_p}{p_n} = \frac{\tau_h}{\tau_e}\frac{n_n}{p_p}\frac{\sqrt{\mu_e\tau_e}}{\sqrt{\mu_h\tau_h}}$$

$$\frac{J_e}{J_h} = \frac{\tau_h}{\tau_e}\frac{n_n}{p_p}\frac{\sqrt{\mu_e\tau_e}}{\sqrt{\mu_h\tau_h}} = \frac{0.15}{25}\frac{5x10^{25}}{1x10^{23}}\frac{\sqrt{0.12x25}}{\sqrt{0.045x0.15}} = 0.016$$

So the emitter efficiency is 0.984