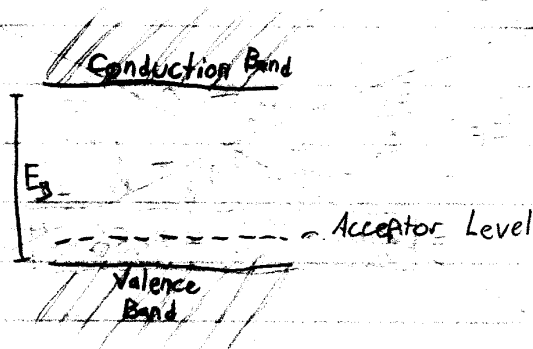


Problem Set 3 Solutions

(a) $N_i = 10^{16} \text{ m}^{-3}$
 $N_A = 10^{23} \text{ m}^{-3}$



with acceptors, conduction will be by holes, i.e. p-type

Assuming all of the acceptor states are filled (a very safe assumption at $T=300\text{K}$), then

$$N_h = N_A$$

and

$$N_e = \frac{N_i^2}{N_h}$$

$$\Rightarrow N_h = 10^{23} \text{ m}^{-3}$$

$$N_e = \frac{(10^{16} \text{ m}^{-3})^2}{10^{23} \text{ m}^{-3}} = 10^9 \text{ m}^{-3}$$

b) $m_e^* = m_h^* = m_0$

From equation 15.13 (it's not too hard to derive)

$$N_e \cdot N_h = N_c N_v \exp\left(-\frac{E_g}{kT}\right)$$

Rearranging to solve for E_g , and using known N_e and N_h values as well as the N_c and N_v expressions:

$$E_g = -k_B \cdot T \cdot \ln\left(\frac{N_e N_h}{N_c N_v}\right) = -(1.38 \cdot 10^{-23} \text{ J/K})(300 \text{ K}) \cdot \ln\left(\frac{10^9 \cdot 10^{23}}{N_c N_v}\right)$$

$$N_c = \frac{2(2\pi m_e^* k_B T)^{3/2}}{h^3} = \frac{2[2\pi(9.11 \cdot 10^{-31} \text{ kg})(1.38 \cdot 10^{-23} \text{ J/K})(300 \text{ K})]^{3/2}}{(6.63 \cdot 10^{-34} \text{ J}\cdot\text{s})^3} = 2.51 \cdot 10^{25} \text{ m}^{-3}$$

$$N_v = \frac{2(2\pi m_h^* k_B T)^{3/2}}{h^3} = 2.51 \cdot 10^{25} \text{ m}^{-3}$$

$$\Rightarrow E_g = (-4.14 \cdot 10^{-21} \text{ J}) \cdot \ln\left[\frac{10^{32}}{(2.51 \cdot 10^{25})^2}\right] = 1.79 \cdot 10^{-19} \text{ J} = 1.1 \text{ eV}$$

c) The donor impurities will, in a sense, compensate 1-for-1 with acceptors, so the semiconductor with

$$N_D = 10^{23} \text{ m}^{-3} \quad \text{and} \quad N_A = 5 \cdot 10^{22} \text{ m}^{-3}$$

will act like a semiconductor doped with

$$N_A = (10^{23} \text{ m}^{-3}) - (5 \cdot 10^{22} \text{ m}^{-3}) = 5 \cdot 10^{22} \text{ m}^{-3}$$

Then,

$$N_n = N_A = 5 \cdot 10^{22} \text{ m}^{-3}$$

$$N_e = \frac{N_i^2}{N_n} = \frac{(10^{16} \text{ m}^{-3})^2}{(5 \cdot 10^{22} \text{ m}^{-3})} = 2 \cdot 10^9 \text{ m}^{-3}$$

Intuitively, we know E_g shouldn't change by doping (and the equation will tell you that).

$$E_g = 1.1 \text{ eV}$$

$$2) a) N_i = 10^{17} \text{ cm}^{-3} = 10^{23} \text{ m}^{-3}$$

Group III element \rightarrow acceptor

$$N_A = 10^{17} \text{ cm}^{-3} = 10^{23} \text{ m}^{-3}$$

Using the assumptions discussed in problem 1:

$$N_p = N_h = \boxed{10^{25} \text{ m}^{-3}}$$

$$N_e = \frac{N_p^2}{N_h} = \frac{(10^{25} \text{ m}^{-3})^2}{10^{23} \text{ m}^{-3}} = \boxed{10^{28} \text{ m}^{-3}}$$

b) In addition to the equilibrium concentrations expected from part (a), there will be 10^9 more holes and 10^9 more electrons per cm^3 .

$$10^9 \text{ cm}^{-3} = 10^{15} \text{ m}^{-3}$$

$$N_h = 10^{23} \text{ m}^{-3} + 10^{15} \text{ m}^{-3} = 1,000,000,001 \cdot 10^{23} \text{ m}^{-3} \quad (\text{not much change!})$$

$$\text{change in hole conc.} = \frac{10^{23} + 10^{15}}{10^{23}} = \boxed{1.00000001, \text{ or } 1 \text{ in } 100 \text{ million}}$$

$$N_e = 10^{28} \text{ m}^{-3} + 10^{15} \text{ m}^{-3} = 1.0001 \cdot 10^{28} \text{ m}^{-3}$$

$$\text{change in elec. conc.} = \frac{10^{28} + 10^{15}}{10^{28}} = \boxed{1.0001, \text{ or ten-thousand fold increase}}$$

c) As we saw in part (b), the hole concentration is pretty unaffected by the light, so the conc. of holes after turning off the light basically remains constant at

$$N_h = \boxed{10^{23} \text{ m}^{-3}}$$

The minority carrier (electron) excess concentration falls off as $\exp(-\frac{t}{\tau})$. After one millisecond, the excess concentration is

$$N_{\text{excess}} = (10^{15} - 10^{17}) \cdot \exp(-\frac{10^{-3} \text{ s}}{3 \cdot 10^{-4} \text{ s}}) = 3.57 \cdot 10^{13} \text{ m}^{-3}$$

$$N_e = 10^{28} \text{ m}^{-3} + 3.57 \cdot 10^{13} \text{ m}^{-3} = \boxed{3.58 \cdot 10^{28} \text{ m}^{-3}}$$

$$3. \quad m_e^* = 0.35 m_0$$

$$m_h^* = 0.5 m_0$$

$$E_f = 9$$

$$N_A = 10^{16} \text{ cm}^{-3} = 10^{24} \text{ m}^{-3}$$

$$N_D = 10^{16} \text{ cm}^{-3} = 10^{22} \text{ m}^{-3}$$

$$E_g = 2.25 \text{ eV}$$

From equation 15.14:

$$N_i = (N_c \cdot N_v)^{1/2} \exp\left(-\frac{E_g}{2k_B T}\right) = \frac{2(2\pi k_B T)^{3/2}}{h^3} \cdot (m_e^* m_h^*)^{3/4} \cdot \exp\left(-\frac{E_g}{2k_B T}\right)$$

Assume Room Temp

$$N_i = \frac{2[2\pi \cdot (1.38 \cdot 10^{-23} \text{ J/K})(300 \text{ K})]^{3/2}}{(6.63 \cdot 10^{-34} \text{ J}\cdot\text{s})^3}$$

$$\cdot [(0.35)(0.5)(9.11 \cdot 10^{-31} \text{ kg})^2]^{3/4} \cdot \exp\left(-\frac{2.25 \text{ eV}}{2k_B T}\right)$$

$$N_i = 8.57 \cdot 10^5 \text{ m}^{-3}$$

note small value for N_i , as we should expect for a large bandgap semiconductor

$$V_0 = \frac{k_B T}{e} \ln\left(\frac{N_A \cdot N_D}{N_i^2}\right)$$

$$= \frac{(1.38 \cdot 10^{-23} \text{ J/K})(300 \text{ K})}{(1.6 \cdot 10^{-19} \text{ coul})} \ln\left(\frac{(10^{24} \text{ m}^{-3})(10^{22} \text{ m}^{-3})}{(8.57 \cdot 10^5 \text{ m}^{-3})^2}\right)$$

$$= \boxed{2.03 \text{ V}}$$

4. Color emitted from an LED is related to the energy of the bandgap, since this is the energy of a photon emitted when an electron and a hole recombine.

$$\text{for GaP, } E_g = 2.3 \text{ eV}$$

$$\text{for GaN, } E_g = 3.4 \text{ eV}$$

As we replace P with N, E_g will increase from 2.3 eV \rightarrow 3.4 eV.

2.3 eV photons correspond to a wavelength of

$$\lambda = \frac{hc}{E} = \frac{(6.63 \cdot 10^{-34} \text{ J}\cdot\text{s})(3 \cdot 10^8 \text{ m/s})}{(2.3 \text{ eV})(1.6 \cdot 10^{-19} \text{ J/eV})} = 539 \text{ nm (green)}$$

3.4 eV,

$$\lambda = \frac{hc}{E} = 365 \text{ nm (blue)}$$

So the LED would go from green to blue as we replace phosphorous with nitrogen.