Homework 12

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Problem 1 A photon of energy 1.6eV is absorbed by GaAs at room temperature: in the process, an electron is excited from the heavy hole band to the conduction band. No phonons are involved. Calculate the energies and length of the wave vectors for the electron and hole involved. Use values from Kittel and the approximate dispersion relations on page 201 of Kittel for the heavy hole.

Solution The data used are $m_{\mathrm{e}} = 0.066m$, $m_{\mathrm{h}} = 0.5m$, and the conservation laws are (note that in conservation laws, the energy and momentum of the hole have negative signs)

$$E_{\mathrm{c}} + \frac{p_{\mathrm{e}}^2}{2m_{\mathrm{e}}} - \mu + \mu - \left(E_{\mathrm{v}} - \frac{p_{\mathrm{h}}^2}{2m_{\mathrm{h}}}\right) = E_{\mathrm{photon}}, \quad p_{\mathrm{e}} - p_{\mathrm{h}} = \frac{E_{\mathrm{photon}}}{c}, \tag{1}$$

and we get

Problem 2 Why does a small concentration of donors or acceptors can have a big impact on the concentration of free carriers in Ge at room temperature (300 K) ?

Solution Because the intrinsic carrier concentration is too small. For Ge, I consult this webpage, and find the heavy hole mass is $m_{\mathrm{ph}} = 0.29m$, and the geometric average of the electron mass is $m_{\mathrm{L}} = 0.222m$, and the band gap can be found from Wikipedia, which is 0.67 eV when $T = 300\,\mathrm{K}$, so we have

$$n_{\mathrm{i}} = 2\left(\frac{k_{\mathrm{B}}T}{2\pi\hbar^2}\right)^{3/2}(m_{\mathrm{e}}m_{\mathrm{h}})^{3/4}\exp\left(-E_{\mathrm{g}}/2k_{\mathrm{B}}T\right) = 7.56\times10^{12}\,\mathrm{cm}^{-3}, \tag{2}$$

which is small compared with usual acceptor or donor concentrations.

Problem 3 3. [20 points] A silicon p-n junction tunnel diode is doped with equal concentrations of donors (n-side) and acceptors (p-side): $N_d = N_a$. What values of N_a and N_d are needed for the depletion region width $(d_n + d_p)$ to equal 50 Å? Assume that you have $\epsilon e\Delta\phi_0 = 0.5\mathrm{eV}$.

Solution Here we use

$$d_{n,p} = 105\left\{\frac{(N_a/N_d)^{\pm1}}{10^{-18}\,(N_d+N_a)}[\epsilon e\Delta\phi]_{\mathrm{ev}}\right\}^{1/2}\ \text{Å} \tag{3}$$

from A&M (29.18). Since $N_a = N_d$, we have $d_n = d_p = 25\,$Å, and therefore $N_a = N_d = 4.4\times10^{18}\,\mathrm{cm}^{-3}$. (Note that in (29.18), the unit of $N_{a/d}$ is cm^{-1}, not m^{-1}; and (29.17) is in Gaussian units.)

Problem 4 A Si p-n junction diode at room temperature has its p-side doped with $N_a = 4\times10^{16}\ \mathrm{cm}^{-3}$ and its n-side with $N_d = 1\times10^{17}\ \mathrm{cm}^{-3}$. The donor and acceptor binding energies are 0.025eV and 0.06eV, respectively. Take $\epsilon e\Delta\phi_0 = 0.5\mathrm{eV}$ and $\Delta\phi_0 = 1\vee$ for Si. (I realize these values seem strange in that $\epsilon < 1$ is implied; but please take these as effective values that are correct for a junction where our simple theory is not quite right: namely, use $\Delta\phi_0$ as the potential change across the junction at equilibrium that then determines the voltage dependent junction wide and take $\epsilon e\Delta\phi_0$ as the key parameter determining the junction width at equilibrium). a) What are the widths of the n - and p-type depletion regions in equilibrium? b) When a forward bias of 0.8 V is applied to this diode, what are the values of the n - and p-type depletion region widths?

Solution

(a) We are under room temperature so it's safe to assume that the doped atoms are fully ionized. Using A&M (29.18) again, we have $d_n = 125.5\,$Å, and $d_p = 313.7\,$Å.

(b) From

$$d_{n,p}(V) = \sqrt{1 - \frac{V}{\Delta\phi}}\,d_{n,p}(0) \tag{4}$$

we have $d_n = 56.1\,$Å, and $d_p = 140.3\,$Å.

Problem 5 The color of an LED is controlled by the direct band gap of the semiconductor used to construct it. In practice, this is done by alloying different semiconductors to change the band gap. Vegard's law applies reasonably well: the size of the band gap is linearly related to the composition of the material; for example, if you make a 50/50 alloy of AIN and GaN with composition $Al_{0.5}Ga_{0.5}$ N then its band gap is the average of the band gaps of AIN and GaN. Assume Vegard's law holds. Also, consult the handout on band gaps on the next page. For questions of practicality, know that trying to make a high-quality junction of two materials whose lattice parameters differ significantly is very hard: when the strain (lattice) mismatch is too high, the interface region between the two materials becomes disorderly and defective to relax the strain, and this degrades performance. The more the strain mismatch, the worse the interface. a) You want to make an LED emit at 620 nm using an alloy of CdS and CdSe. What composition should you use? b) Your supply of CdS is depleted due to supply chain issues. However, you do have a supply of CdSe, ZnS, and ZnSe. Which combination is the best choice for making a high-quality LED emitting at 620 nm ? Why? c) Your friend has an alternative approach: they have a supply of GaP and GaAs and plan to make an alloy to create the 620 nm LED. What is a problem with their plan?

Solution

(a) The energy of a 620 nm photon is 2.0 eV. The energy gap of CdSe is 1.7 eV, and the energy gap of CdS is 2.5 eV, so the percentage of CdSe should be 62.5 %, and the percentage of CdS should be 37.5 %.

(b) ZnSe and CdSe should be used. The percentage of CdSe is 72.7 %, and the percentage of ZnSe is 27.3 %. ZnS is not used because the difference between the lattice constants of it and CdSe is too large.

(c) The problem is GaP has an indirect band gap, and therefore isn't very efficient in light emission.