University of Sheffield

Department of Electronic and Electrical Engineering

EEE207 Semiconductors for Electronics and Devices

Problem Sheet 5

1. Given that germanium is an indirect-gap semiconductor with a band gap 0.67eV, sketch the expected variation of optical (light radiation) absorption with wavelength. How does it differ from that of GaAs, which is a direct-gap material with energy gap 1.4eV?

2. A p-n junction LED is made from GaAs (energy gap 1.4eV). A current of 10mA flows in the forward direction; calculate the light power output, if all the current flow is due to direct electron-hole recombination, and all recombination results in photon emission.

In fact, only about 0.1% of this power is transmitted to observers. Why?

How does the light output from this LED compare with sunlight intensity (~ 10W over a square 300 × 300 mm^2) or moonlight (~ 5×10^{-5}W over a square 300 × 300 mm^2), if the diode has an area of 1mm^2?

3. In a simple model of an LED, electrons are assumed to fall from the bottom of the conduction band to the top of the valence band, emitting a photon with $\omega = E_g / \hbar$. In fact, because of thermal excitation, electrons in the conduction band have a distribution of energies, but with an average energy of $3kT/2$ above the band edge; a similar statement applies to the distribution of holes. How does this affect the spectrum of emitted photons? Can you sketch the approximate shape of the spectrum of emitted light (for simplicity plotted vs. ω)? Do the same principles apply to the radiation from a semiconductor laser?

4. *Light (having $\omega > E_g / \hbar$) falls on a rectangular slab of intrinsic semiconductor. The slab receives a* total power P of illumination. Holes and electrons have mobilities μ_h and μ_e, and lifetimes of τ_h and τ_e respectively. Find an expression for the resistance of the semiconductor measured parallel to sides having length L, if the quantum efficiency is η (i.e. only one in every $1/\eta$ photons will produce an electron-hole pair).

5. [This question is quite tricky!] A long thin rod of n-type semiconductor is parallel to the x direction with one end fixed at $x = 0$, and is illuminated uniformly over the region $0 < x < a$. Show that the excess electron density, Δn, is given approximately by

$$\Delta n = \begin{cases} g\tau \times [1 - \exp(-a / L_e)\cosh(x / L_e)], & \text{for } 0 < x < a \\ g\tau \sinh(a / L_e)\exp(-x / L_e), & \text{for } x > a \end{cases}$$

where g is the carrier generation rate in the illuminated region (which can be assumed to be much greater than the thermal generation rate), τ is the recombination time, and L_e is the diffusion length for minority electrons. [Hint: you will need to solve the diffusion equation, $L_e^2(d^2n/dx^2) = (n - n_0)$, in the two regions of interest. What are the boundary conditions at $x = 0$, at $x = a$, and as $x \to \infty$?]

6. This problem revises your understanding of optical refraction and of total internal reflection. An optical fibre consists of a cylinder of glass (the core, refractive index n_1) surrounded by a different type of glass (refractive index n_2), also cylindrically symmetric. The end of the fibre is perpendicular to the cylinder axis. Show that light, incident on this end at an angle θ to the axis is guided *inside the core* (without appreciable loss, i.e. all changes of light direction inside the fibre occur by total internal reflection) when $|\sin\theta| < (n_1^2 - n_2^2)^{1/2}$. What happens when $n_1 < n_2$? Under what conditions is energy lost from the fibre?

Numerical Answers

1. Radiation 'absorption edges' at 1.85μm, 0.887μm
2. Diode: 14mW mm^{-2}, observe 0.014mW mm^{-2}; Sun: 0.11mW mm^{-2}; moon: 5.5×10^{-7}mW mm^{-2}
3. Mean ω is shifted by $3kT/\hbar$
4. $\hbar\omega L^2/[P\eta e(\tau_e\mu_e + \tau_h\mu_h)]$
6. Energy lost if $|\sin\theta| > (n_1^2 - 1)^{1/2}$

Charge on electron:	$-1{\cdot}602\times10^{-19}$C
Free electron rest mass:	$m_0 = 9{\cdot}110\times10^{-31}$kg
Speed of light in vacuum:	$c = 2{\cdot}998\times10^{8}$m s^{-1}
Planck's constant:	$h = 6{\cdot}626\times10^{-34}$J s
Boltzmann's constant:	$k = 1{\cdot}381\times10^{-23}$J K^{-1}
Melting point of ice:	0°C = 273·2K
Permittivity of free space:	$\varepsilon_0 = 8{\cdot}854\times10^{-12}$F m^{-1}
Permeability of free space:	$\mu_0 = 4\pi\times10^{-7}$H m^{-1}