S-104.3310 Optoelectronics **Second Exam** **31.7.2006**

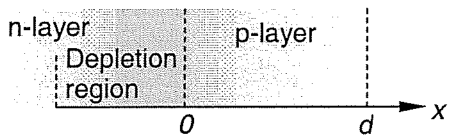
1. Explain **briefly** the following terms: a) molecular beam epitaxy b) VCSEL c) Auger recombination

2. a) Describe **briefly** some advantages of quantum wells lasers compared to bulk lasers.
b) Calculate the transition energy between the 1e and 1hh levels of a 40Å InGaAs QW as well as the corresponding wavelength. Use the infinite square potential well approximation and the following parameters for InGaAs: $E_g = 0.74$ eV, $m_{hh} = 0.5m_0$, $m_e = 0.045m_0$.

3. Calculate the electron and hole concentration in a n-doped silicon sample ($N_D = 10^{18}$ cm^{-3}) at T=300K. Use the following effective density of states $N_C = 2.9\times10^{19}$ cm^{-3} and $N_V = 1.1\times10^{19}$ cm^{-3} as well as $E_g = 1.12$ eV. Suppose that all donor atoms are ionized.

4. The quantum efficiency of an InGaAs avalanche photodiode is 0.8 at λ=1.55 μm. The multiplication coefficient is 40 and the thickness of the multiplication region is 1 μm.
a) Calculate the generated photocurrent when the input optical power is 1 μW.
b) How thick should the multiplication region be in order to double the multiplication coefficient? Suppose than only electrons multiply themselves.

5. A LED is ruled by the following equations:



$$\frac{\partial n}{\partial t} = \frac{-n(x,t)}{\tau} + D_e \frac{\partial^2 n}{\partial x^2} \quad (1) \qquad J(t) = qD_e \left.\frac{\partial n}{\partial x}\right|_{x=0,t} \quad (2)$$

where, n the electron concentration in the p-layer, J the current density through the device, D_e the electron diffusion constant, and τ is the **radiative** recombination time. Light is emitted only from the p-layer.

a) Calculate the electron concentration $\overline{n}$ at quasi-equilibrium as a function of $J = \overline{J} = cste$ and $L_e = \sqrt{D_e \tau}$.

b) Demonstrate that if the p-layer is considered as infinitely thick the photon flux $\overline{\phi}$ emitted from the LED at quasi-equilibrium is given by:

$$\overline{\phi} = \eta_e\left(-\overline{J}/q\right)\cdot\left(1-e^{-d/L_e}\right) \quad (3)$$

with η_e the extraction efficiency and d the thickness of the p-layer.

6. We consider the same LED as in the previous exercise. The thickness d of the p-layer is considered as infinite. The current through the LED is modulated with a small sinusoidal signal so that $J(t) = \overline{J} + \tilde{J}e^{j\omega t}$, $n(t) = \overline{n} + \tilde{n}(\omega)e^{j\omega t}$ and $\phi(t) = \overline{\phi} + \tilde{\phi}(\omega)e^{j\omega t}$.

a) Show that the relative modulation response $H(\omega) = \left|\tilde{\phi}(\omega)/\tilde{\phi}(0)\right|$ is given by:

$$H(\omega) = \frac{1}{\left[1+\omega^2\tau^2\right]^{1/2}} \quad (4)$$

Hint: calculate first $\tilde{n}(\omega)$ based on equations (1) and (2) using $L_e(\omega) = \sqrt{D_e\tau/(1+j\omega\tau)}$.

b) Based on equation (4), give the expression for the bandwidth B of the LED (in Hz).

Hint: the bandwidth can be defined as the frequency above which $10\log H \leq -3dB$.