7. Tutorial on Optical Sources and Detectors

June 19th 2012

Problem 1: Germanium on Silicon Laser

Just like silicon, germanium is also an indirect semiconductor. The band structure of bulk germanium is depicted in Figure 1.

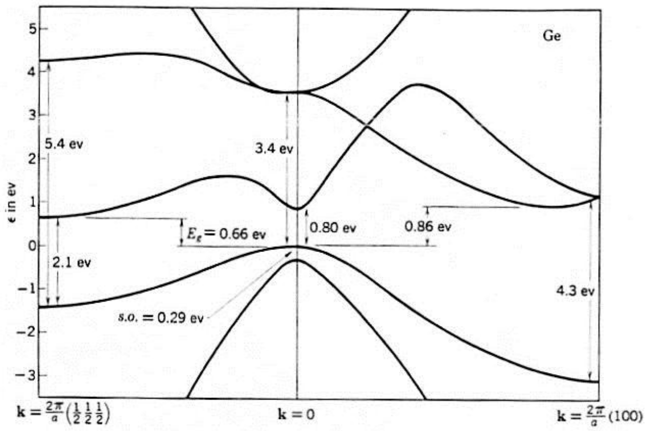

Figure 1: Band structure of bulk germanium. The indirect bandgap energy is W_G = 0.66 eV, a direct transition is possible for $W_G' = 0.80\text{eV}$

a) Calculate the wavelengths that correspond to the indirect and the direct transition of germanium.

b) In a recent publication it has been shown that it is possible to obtain light emission and even lasing from germanium grown on silicon. Find and read the publication:

   Liu et al., "Ge-on-Si laser operating at room temperature", Opt. Lett. Vol. 35, Issue 5, pp. 679-681 (2010).

   In order to access the paper, you need to be within the KIT network (on campus or via VPN connection)

   Explain how the indirect band structure of germanium has been changed to that of a so-called pseudodirect-bandgap semiconductor. Why is this not possible for silicon?

Problem 2: Fabry-Perot Laser Diode

For building a Fabry-Perot laser diode that emits a wavelength of λ = 870 nm a double heterostructure was chosen with p-GaAs as the active zone which is surrounded by an n-(Ga,Al)As, and a p-(Ga,Al)As. The active layer has a thickness d = 0.2 µm and refractive index n_1 = 3.59. The surrounding layers have both refractive index n_2 = 3.45. The laser diode is L = 500 µm long and the active zone has a width of b = 3 µm.

a) What are the advantages of using such a double heterostructure as opposed to a homojunction?

b) For a slab waveguide the field concentration factor Γ of the optical field in the waveguide core can be approximated by

$$\Gamma = \frac{2V^2}{1+2V^2}, \quad V = \frac{d}{2} k_0 \sqrt{n_1^2 - n_2^2}$$

where V is the normalized frequency, d is the thickness of the waveguide core and $k_0 = \omega / c$ is the free-space wavenumber of the optical signal.

Plot the field concentration factor of the above mentioned laser diode as a function of waveguide thickness for the values of $d = 0$ to $d = 1$ µm using commercial software (e.g. Matlab, available at the SCC or can be downloaded from Asknet).

c) The threshold current density J_{th} is given by

$$J_{\text{th}} = \frac{edn_{c,\text{tr}}}{\tau_{\text{eff}}} \left[1 + \frac{\alpha_{\text{int}} + \alpha_R}{\Gamma(d) g_0} \right]$$

where $n_{c,\text{tr}} = 1.1 \cdot 10^{18}\,\text{cm}^{-3}$ is the transparency carrier density, $\tau_{\text{eff}} = 1\,\text{ns}$ is the effective carrier lifetime, $g_0 = 330\,\text{cm}^{-1}$ is the differential gain and $\alpha_{\text{int}} = 25\,\text{cm}^{-1}$ is the loss of the waveguide. The distributed loss parameter α_R accounts for the light that is emitted through the mirrors via $e^{-\alpha_R L} = R$. Assume that the power reflection factors R of the facets can be obtained by the Fresnel reflection coefficient of the facet boundary formed by the active region and air which is given by $R = \left(\frac{n_1 - n_{air}}{n_1 + n_{air}} \right)^2$

Plot the threshold current density as a function of the waveguide thickness d for the same values as in part b)

d) Explain why J_{th} increases for both very small and very large values of d. Calculate the threshold current I_{th} for $d = 0.2$ µm.

e) Sketch the output power spectrum of the emitted light for a nonzero current density below threshold and for a current density much higher than threshold.

f) The optical power and external power efficiency η_{ext} can be calculated via

$$P_{\text{out}} = \frac{N_P hf}{\tau_R} \quad \text{and} \quad \eta_{\text{ext}} = \frac{P_{\text{out}}/hf}{I/e}.$$

Neglecting spontaneous emission and gain compression the output power can be expressed as

$$P_{\text{out}} = hf \eta_d \frac{(I - I_{th})}{e}$$

where the differential or slope efficiency is given as $\eta_d = \eta_{\text{int}} \frac{\tau_P}{\tau_R}$ with $\tau_p^{-1} = v_g (\alpha_{\text{int}} + \alpha_R)$ the photon lifetime in the resonator, $\tau_R^{-1} = v_g \alpha_R$ the part of the photon lifetime that is related to the mirror reflectivities and η_{int} the internal quantum efficiency.

Assuming that $\eta_{\text{int}} = 95\%$, what is the optical output power when the laserdiode is driven with $I = 200$ mA? How many photons per second are emitted from the laser facets?

g) What is the external power efficiency η_{ext}? How does this value compare to the external power efficiency of an LED?