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.

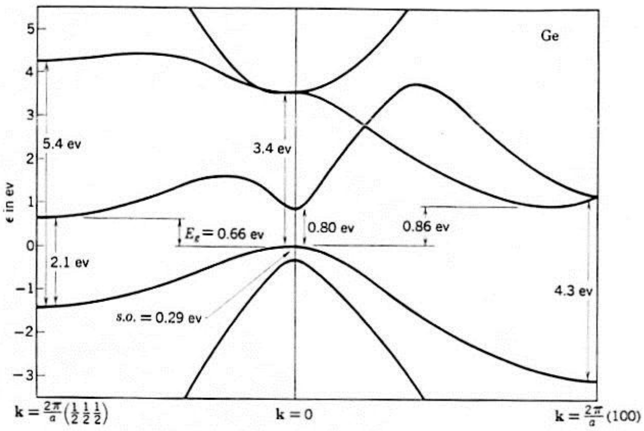

Figure 1: Band structure of bulk germanium. The indirect bandgap energy is $W_G = 0.66$ eV, a direct transition is possible for $W'_G = 0.80\text{eV}$

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

➔ The indirect transition corresponds to $\lambda = hc/W_G = 1.88\mu\text{m}$ and the direct transition to $\lambda = hc/W'_G = 1.55\mu\text{m}$.

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?

➔ The article can be found here: http://www.opticsinfobase.org/ol/abstract.cfm?id=196081
Possibilities for conducting a literature research:

http://scholar.google.de/
http://ieeexplore.ieee.org
http://www.opticsinfobase.org/
http://www.webofknowledge.com/

In general more than one of these search engines should be used when doing a literature search (e.g. for a Master thesis). Some engines are specialized on a particular field and might not give you all relevant results whereas other search engines are very general and might give you too many results where a lot are not applicable for your search case. It is recommended to use the possibilities of advanced searches and wildcards as explained in the help sections of the above links. Another helpful tool is the possibility to download citation information of the search results (e.g. in bibtex or endnote format). This helps creating a database (e.g. with jabref or endnote) of the most important publications, which can then be used for correct citation of articles in a bachelor or master thesis.

➔ In the publication mentioned above the band structure of Germanium, see Figure 2 (a) is altered via two techniques. The first is the tensile strainthat is incorporated into the crystal lattice by the lattice mismatch to the Silicon on which the Germanium is grown. This shrinks the direct bandgap of Ge to 0.76eV. The conduction band valley is then populated by strong n-type doping with 10^{19} cm^{-3} phosphorous, see Figure 2 (c).

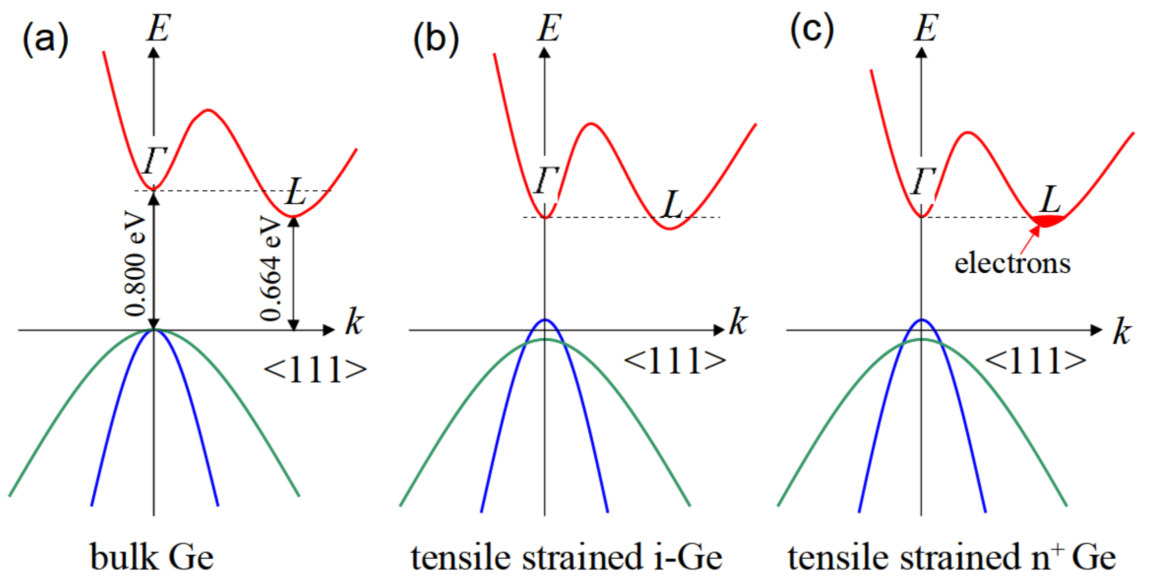

Figure 2: Band structure of (a) bulk Ge, (b) tensile strained Ge without doping (c) highly n-doped and tensile strained Ge. From Liu et al., "Tensile-strained, n-type Ge as a gain medium for monolithic laser integration on Si," Opt. Express 15, 11272 (2007).

Problem 2: Fabry-Perot Laser Diode

For building a Fabry-Perot laser diode that emits a wavelength of $\lambda = 870$ 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?

➔ Heterostructures confine both the excited carriers and the photons to the same space. Hence efficient recombination and stimulated light emission is achieved. The reason for this is that the bandgap energy is inversely proportional to the refractive index. Therefore the low bandgap active region that is surrounded by large bandgap semiconductors accumulates the excited carriers and forms an electro-magnetic waveguide.

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).

➔ See plot in part c)

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)

➔

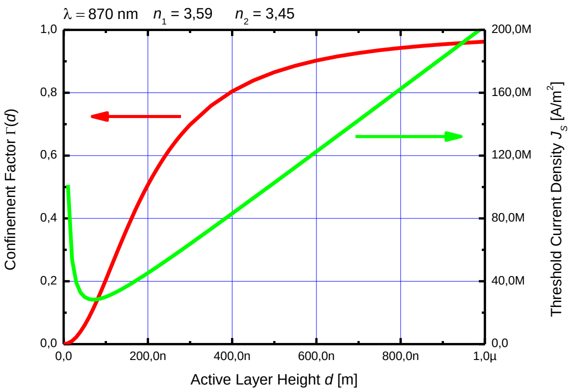

Figure 3 Confinement factor and threshold current density as a function of the active layer height. Parameters are λ = 870 nm, n_1 = 3.59 and n_2 = 3.45.

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.

➔ For very small active layer heights the confinement factor is very small and therefore a large current density is required to obtain lasing. For very large active layer heights it is more difficult to achieve inversion since the volume of the active layer increases.

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

$$d = 0.2\text{nm}$$

$$n_{c,\text{tr}} = 1.1\cdot 10^{18}\text{cm}^{-1}$$

$$\tau_{\text{eff}} = 1\text{ns}$$

$$\alpha_{\text{int}} = 25\text{cm}^{-1}$$

$$\alpha_R = -\frac{2}{L}\ln\left(\frac{n_1-n_{\text{air}}}{n_1+n_{\text{air}}}\right) = 22.9\text{cm}^{-1}$$

$$\lambda = 850\text{nm}$$

$$V(d) = \frac{d}{2}k_0\sqrt{n_1^2-n_2^2} = 0.72$$

$$\Gamma(d) = \frac{2V^2}{1+2V^2} = 0.5$$

$$g_0 = 330\text{cm}^{-1}$$

$$\Rightarrow J_{\text{th}} = 4526.8\frac{\text{A}}{\text{cm}^2}$$

$$L = 500\mu\text{m}$$

$$b = 3\mu\text{m}$$

$$\Rightarrow I_{\text{th}} = J_{\text{th}}Lb = 68\text{mA}$$

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.

➔

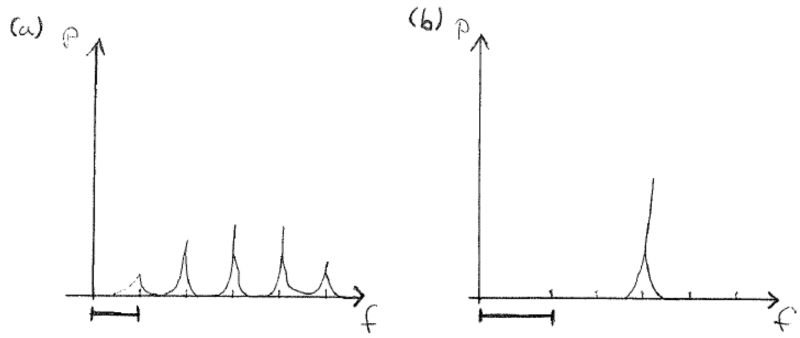

Figure 4: Output spectra of a Fabry-Perot laser diode (a) Below threshold and (b) above threshold. The marker below indicates that the resonances are shifted as the output power increases.

Figure 4 shows the output power spectra of a laser diode for the cases (a) below threshold and (b) above threshold. Below threshold there are several longitudinal modes within the gain bandwidth, whereas above threshold the resonance frequencies are shifted and only one longitudinal mode is generated since this one experiences the highest gain and therefore reduces the gain of all the other modes.

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 η_{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?

➔

$$P_{\text{out}} = 20.7\text{mW}$$
$$\frac{N_P}{1\text{s}} = \frac{P_{\text{out}}}{2 \cdot hf} = 4.8 \cdot 10^{16}\,\text{s}^{-1}$$

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

➔ $\eta_{\text{ext}} = 14.5\%$

This is about an order of magnitude higher than for an LED. This stems from the fact that photons that are backreflected from the facets are not lost as in an LED, they just leave the laser cavity at a later point in time.

Questions and Comments:

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