6.5. Absorption Associated with Extrinsic Charge Carriers

Extrinsic electrons (or holes) are associated with dopands or impurities (or defects). Thus, the free extrinsic charge carrier concentration in doped semiconductors is much higher than the intrinsic one and is not so sensitive to temperature.

However, at low enough temperatures the extrinsic charge carriers become loosley bound to the impurities, too, leading to temperature dependent charge carrier concentrations.

6.5.1. Free-Carrier Absorption in Doped Semiconductors

We consider the free-carrier contribution to the complex dielectric function of semiconductors within the free-electron or Drude model.

The main difference compared to the free charge carriers of simple metals is the carrier concentration N_c, in semiconductors typically less than 10^{20} cm^{-3}, but in metals at around 10^{22} cm^{-3}. Thus, the plasma frequency of free carriers is at the infrared (IR) or visible/ultraviolet (UV), respectively.

Vapaaelektronimallin plasmavärähtelyn kulmataajuus ω_p saadaan relaatiosta

$$\omega_p^2 = N_c e^2 / \varepsilon_0 m,$$

if dissipation is not included.

Within the classical free-electron model (following the treatment of phonons above, but neglecting harmonic forces) including dissipation for absorption we can write the equation of motion of electrons as

Due to absorption $\varepsilon(\omega)$ is complex and can be decomposed to

Phenomenologically the absorption is described by scattering with the relaxation time $\tau = \gamma_c^{-1}$. This scattering is interband transition, which needs to involve a phonon to conserve both energy and momentum.

The imaginary part $\varepsilon_i(\omega)$ can be used to evaluate the absorption coefficient, which is a useful way to study free-carrier scattering mechanisms in semiconductors.

/. Optical Properties II

The previous chapter dealt with "optical phenomena" with one frequency, only. The related materials properties were possible to be described in terms of the complex dielectric function.

Here, we consider phenomena where the incident and response wave frequencies may differ due to more complicated processes. Scattering and emission of light are typical of such. *Photoluminescence* is an emission process following the incident absorption. *Raman* and *Brillouin scattering* are inelastic processes, where the wavelength of scattered light is changed.

7.1. Emission Spectroscopies

Depending on the excitation process or creation of e–h pairs the luminescence is called

- electro-
- photo-
- thermo-
- cathodo-

The luminescence itself is a radiative recombination of the e–h pairs, which can be stimulated or spontaneous.

<u>Einstein's A and B coefficients</u>

Let us consider matter with two quantum levels and transitions between these. Assume thermal equilibrium with black body radiation at temperature T, with energy density

$$\rho_e(\nu) = \frac{8\pi h\nu^3 n_r^3}{c^3\left(e^{-h\nu/kT} - 1\right)},$$

where n_r is the refractive index of the medium.

From the principle of detailed balance it follows (Problem 7.1)

$$B_{nm} = B_{mn} \tag{7.1a}$$

and

$$A_{nm} = \frac{8\pi h\nu^3 n_r^3}{c^3} B_{nm}. \tag{7.1b}$$

The total emission rate (transition probablility × occupancy) is

$$R_{nm} = N_n\,[A_{nm} + B_{nm}\,\rho_e(\nu)], \tag{7.2}$$

where $\rho_e(\nu)$ is the radiation energy density at ν.

With the quantized electromagnetic field. occupaton number N_p (number of photons), the emission rate becomes

$$\begin{aligned} R_{nm} &= N_n\,A_{nm}\,[1 + (B_{nm}/A_{nm})\,\rho_e(\nu)] \\ &= N_n\,A_{nm}\,[1 + N_p]. \end{aligned} \tag{7.3}$$

Now, consider spontaneous e–h pair recombination, i.e., set $N_p = 0$, and $N_n \rightarrow f_c(1 - f_v)$, the "joint occupation" of conduction and valence bands.

Then, the emission rate becomes

$$R_{cv} = A_{cv}\,f_c(1 - f_v). \tag{7.4}$$

By denoting absorption rate by P_{vc} and photon density by

$$\rho(\nu) = \rho_e(\nu) / h\nu$$

and ignoring the (negligible) stimulated emission we can write the Roosbroek–Shockley relation

$$P_{vc}(\nu)\,\rho(\nu) = R_{cv}. \tag{7.5}$$

As the absorption coefficient α relates to absorption rate as