In heavily doped semiconductors the emission spectra are modified by additional affects: *bandtail states* within the gap, *bandgap shrinkage* (or *renormalization*) and filling up of the near-bandgap states.

At low temperatures the emission is strongest from the lowest lying levels, such as defect levels inside the band gap. Such defects are called *radiative recombination centers.*

The luminescence process involves three consequent but separate steps:

- excitation
- thermalization
- recombination

Thermalized luminescence reflects the band structure and other electronic energy levels of the semiconductor. Intensities are temperature dependent, however.

Hot luminescence is emitted from nonthermalized charge carriers and typically has some correlation with the initial excitation process.

7.1.1. Band-to-Band Transitions

Direct band gap semiconductors are strong emitters of band gap light through e–h pair recombination leading to short radiative recombination (life)time $\tau_r \approx \mu s$ in intrinsic semiconductors. In indirect band gap semiconductors the radiative lifetime is much longer.

Silicon emits light more efficiently in porous form or as nanocrystals, which is not fully understood, yet.

The recombination rate and photon emission rate is

$$n_e n_h / \langle \tau_r \rangle ,$$

where n_e and n_h are the charge carrier concentrations and $\langle \tau_r \rangle$ is the average radiative lifetime.

For the *minority carrier radiative lifetime* holds

$$1 / \tau_{rad} = n_{maj} / \langle \tau_r \rangle , \qquad (7.8)$$

where n_{maj} is the majority carrier concentration, in case of intrinsic semiconductor equal to n_i.

Table 7.1. Minority carrier radiative lifetimes τ_{rad}

According to (7.8) and Table 7.1 τ_{rad} can be decreased by increasing the majority carrier concentration. There is a limit to this, however, when the entire band becomes populated. For GaAs this limit is about 0.31 ns. This limit is not valid for stimulated emission lifetime, as stimulated emission depends on the photon density. It is not unusual to find stimulated radiative lifetimes of less than 0.1 ps.

As the recombination rates of different processes are additive, if the charge carrier concentrations are not effected too much, for the total recombination lifetime (decay rate) we may write

$$1 / \tau_{tot} = 1 / \tau_{rad} + 1 / \tau_{nonrad} , \qquad (7.9)$$

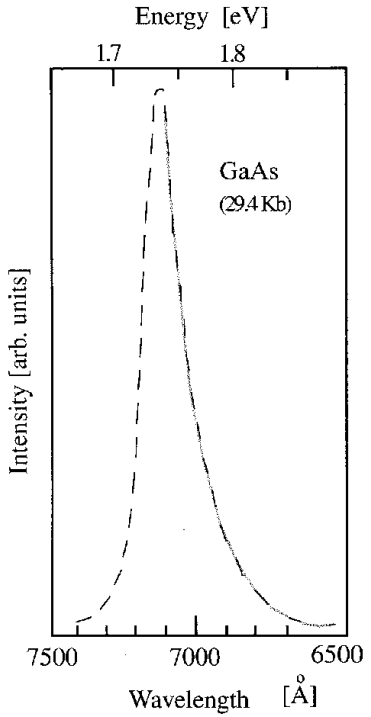
where τ_{nonrad}^{-1} is the recombination rate due to nonradiative processes. The nonradiative processes usually relate to phonons and result in excitation energy transformation to heat.

The shape of a typical band-to-band PL emission spectrum is obtained from (7.4)

$$I_{PL} = R_{cv} = A_{cv} f_c(1 - f_v)$$

by (6.57)

$$A_{cv} \propto D_j \propto \begin{cases} (\hbar\omega - E_g)^{1/2} \\ 0 \end{cases}$$



7.2. Light Scattering Spectroscopies

8. Photoelectron Spectroscopy

Next we consider higher energy excitations, beyond 10 eV and in many cases involving core electrons.

First, however, we can mention the quantized valence electron plasma oscillation excitations or *plasmons,* $\hbar\omega_p$, where

$$\omega_p^{\,2} = N_v e^2 / \varepsilon_0 m \qquad (8.1)$$

and N_v is the valence electron density and m is the free electron mass. For a typical terahedrally coordinated semiconductor $\hbar\omega_p \approx 15 - 16$ eV. This is known as vacuum ultraviolet (VUV) region.