Recombination Channels

Advanced

High Injection Approximations for Recombination Rates

- Since optoelectronic devices usually are made to produce *plenty* of light, the deviation of the carrier concentrations from equilibrium in the recombination zonemust be large to obtain large recombination rates and thus light
  - If we write the concentrations as $n_{e,h} = n_{e,h}(\text{equ}) + \Delta n_{e,h}$, we now may use *the simplest possible approximation* called **high injection approximation**:

$$\Delta n_{e,h} \gg n_{min}(\text{equ})$$

  - i.e. the minority carrier concentration is far *above* equilibrium.
- The surplus carriers contained in $\Delta n_{e,h}$ are always *injected* into the volume under consideration (called **recombination zone** or **recombination volume**), usually by forward currents across a junction. They always must come in equal numbers, i.e. in pairs to maintain charge neutrality; otherwise large electrical fields would be generated that would restore neutrality. We thus have

$$\Delta n_e = \Delta n_h$$

  - The recombination volume usually is the space charge region of a junction or an other volume designed to have *low carrier concentrations* in equilibrium, cf. the picture in the backbone. Since the equilibrium concentration of both carrier types in the **SCR** is automatically very low, we may easily reach the high injection case.
- The surplus concentration of carriers decays with a characteristic lifetime τ_{hi}. For the recombination rate R we have in analogy to "normal" recombination more close to equilibrium:

$$R = \frac{\Delta n}{\tau_{hi}}$$

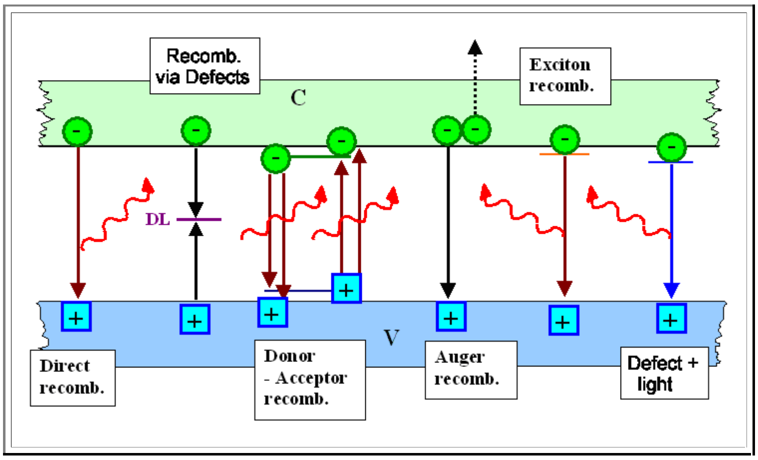
  - The only difference is that the high-injection life time τ_{hi} can be quite different from the equilibrium minority carrier life time. If τ_i is the (high-injection) life time of recombination channel No. i, τ_{hi} is given by

$$\frac{1}{\tau_{hi}} = \Sigma_i \frac{1}{\tau_i}$$

  - The important thing for optimizing **LED's** and Laser is that the τ_i are not constants but depend on the degree of injection as we will see.

Some Specifics of Recombination Channels

- Let's repeat the picture from the backbone to have a listing of the more important recombination channels



- Now let's look at the more mportant recombination channels and their dependence on the injection ratio, i.e. the carrier concentration

The **band-band recombination channel** is easy to understand:

- A large number of electrons and holes finds themselves in some volume of a semiconductor at concentrations far above equilibrium. They are running around in a random matter and every now and then a hole and an electron get real close on their ***perambulations*** and recombine. The probability for this to happen is clearly proportional to the concentration $n_{e,h}$ electrons and holes which as we have postulated above is Δn for both carrier types.
- the recombination rate $R_{b\text{-}b}$ have for the band-band recombination channel is thus given by

$$R_{b\text{-}b} = B_{b\text{-}b} \cdot n^2$$

- The proportionality constant B is occasionally also called a **recombination coefficient**.

If we now look at the **recombination channel via defects** (also called "**deep level**" recombination because the defect must have a energy level deep in the bandgap).

- The story was that an electron on its random migration might encounter a defect, e.g. an impurity atom with an energy level somewhere in the bandgap which it occupies and now is trapped and mellow (low in energy, at least for some time). A hole, somewhat later, also finds the impurity atom plus the electron unable to run away, and happily recombines with the electron. In other words: a girl, wandering around at random finds an irresistible café and sits down for a while. A boy, coming accidentally by the café, seeing the girl trapped there and in a mellow mood, knows what to do... This also means that *no light is produced*
- We obtain a rather simple relation for the recombination rate R_{defect}

$$R_{defect} = B_{dl} \cdot n_{dl} \cdot n$$

- With B_{dl} = recombination coefficient for this case. We have a proportionality to the density of defects and the density of carriers, giving the rate that an electron (or hole) is trapped by a defect. The rest, recombination with the opposite carrier, happens "automatically"

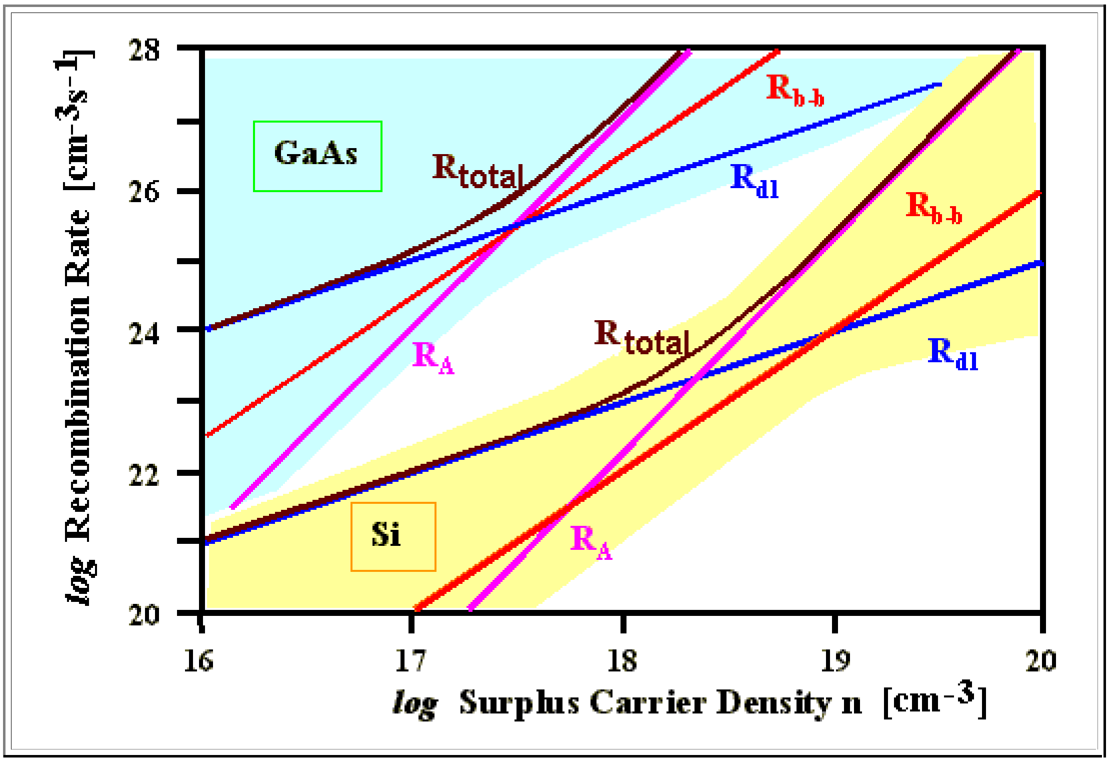
If we omit the recombination from donor and acceptor energy levels (which is quite similar to band-band recombination anyway) and the "exotic" recombination via excitons, we only have to consider "**Auger recombination**".

- In this case the energy of the recombination event is transferred to another electron in the conduction band, which then looses its surplus energy by "thermalization", i.e. by transferring it to the phonons of the lattice. This means that *no light is produced*.
- It also means that we have two have two electrons and one hole at the same place at the same time or that the Auger recombination rate R_A is given by

$$R_A = B_A \cdot n^3$$

Taken everything together we see that we have recombination rates for the major recombination channels that depend on the first, second and third power of the carrier concentration n

If we plot the total recombination rate as a function of carrier density (in a double log plot) with the proper proportionality constants (wherever they come from) and some assumption for defect densities for **GaAs** and **Si**, we obtain the following highly informative picture.



- The recombination rate in **Si** is generally far lower than in **GaAs** and for carrier concentrations **<≈ 10^{18} cm^{-3}** dominated by defect recombination.
- In both cases we can increase the relative strength of radiative band-band recombination by decreasing defect recombination, i.e. by making the semiconductor more pure and perfect and by not allowing too large carrier concentrations.
- Here we have the explanation for the fact that very good solar cells, having by definition very low defect recombination rates, will show measurable luminescence if a large carrier concentration is introduced via an intensive flash of light. This effect is presently (**2008**) exploited for the characterization of solar cells.