5.2 Light and Semiconductors

5.2.1 Total Efficiency of Light Generation

Contributions to the Total Efficiency

- We will now give some thought to the second and third question raised before: *How much light is produced by recombination?* This raises the question for the value of the quantum efficiency η_{qu} mentioned before, and the total or external efficiency η_{ext} in absolute terms (third question).
  - First we will define the quantum efficiency again (and somewhat more specifically) and relate it to some other efficiencies.
  - The **quantum efficiency** η_{qu} is defined as

$$\eta_{qu} = \frac{\text{Number of photons generated in the recombination zone}}{\text{Number of recombining carrier pairs in the recombination zone}}$$

  - We already know that, it could be expressed as

$$\eta_{qu} = \frac{1}{1 + \tau_{rad} / \tau_{non\text{-}rad}}$$

- In the high injection approximation the number of carriers is about equal to the number of carriers injected (across a junction) into the recombination zone.
  - That part of the total recombination occurring via a radiative channel determines the quantum efficiency. However, the surplus carriers in the recombination zone have one more "channel", not considered so far, for disappearing from the recombination zone: *They simply move out*!
  - In other words: parts of the injected carriers will simply flow across the recombination zone and leave it at "the other end".
- This effect can be described by the **current efficiency** η_{cu}; it is defined as

$$\eta_{cu} = \frac{\text{Number of recombining carrier pairs in the recombination zone}}{\text{Number of carrier pairs injected into the recombination zone}}$$

- We now define the **optical efficiency** η_{opt} as

$$\eta_{opt} = \frac{\text{Number of photons in the exterior}}{\text{Number of photons generated in the recombination zone}}$$

  - The optical efficiency takes care of the (sad) fact that in most devices a large part of the photons generated become reabsorbed or are otherwise lost and never leave the device.
- The total or **external efficiency** η_{ext} now simply is

$$\eta_{ext} = \eta_{opt} \cdot \eta_{qu} \cdot \eta_{cu}$$

  - In other words: The external efficiency is limited because not all injected carriers recombine, not all recombinations produce photons, and not all photons leave the material.
- If we want to optimize the external efficiency, we must work on all three factors - none of them is negligible.
  - We already "know" how to optimize the quantum efficiency η_{qu} by looking at the equation above. We must look for the best combination of materials producing radiation at the desired wavelength, and then dope it in such a way as to maximize the radiative channel(s) by minimizing the corresponding lifetimes. While this is not easy to do in practice, it is clear in principle.

- We do not yet know how to attack the two other problems: Maximized current efficiency and maximized optical efficiency. And theses problems are far from being solved in a final, or just semi-final way - intense world-wide research efforts center on new solutions to these problems.
  - While there are no general solutions to these problems and only some useful equations, a few general points can still be made. We will do this in the remainder of this subchapter for the current efficiency and in a separate subchapter for the optical efficiency.

Current Efficiency

- The question to ask is: Why is the current efficiency *not* close to **1** in any case?
  - After all, if we consider a simple **p–n** junction biased in forward direction in a direct semiconductor (e.g., **GaAs**), we inject electrons into the **p**-part and holes into the **n**-part, where they will become minority carriers. Some of the injected carriers will recombine in the space charge region, all others eventually in the bulk region.
  - While the quantum efficiency may be different in the different regions, because the strength of the recombination channels depends on the carrier density which is not constant across the junction, we still could assign some kind of mean quantum efficiency to the diode so that $\eta_{cu} = 1$.
  - However, we defined the efficiencies relative to a "*recombination zone* ", i.e we are not interested in radiation produced elsewhere for various reasons (to be discussed later). If we take the recombination zone to be identical to the **SCR**, only that part of the injected carriers that recombines in the **SCR** will contribute.
  - This is exactly that part of the forward current that we had to introduce to account for real ***I-V***-characteristics of **p–n** junctions – cf. the simple and advanced version in the relevant modules.
  - That part of the current that injects the carriers which *recombine in the SCR* was given by

$$j_{rec}\,(SCR) = \frac{e \cdot n_i \cdot d}{2\tau} \cdot \exp\frac{e \cdot U}{2kT}$$

  - ***d*** was the width of the **SCR**.
- The current efficiency in this case would then be given by

$$\eta_{cu} = \frac{j_{rec}}{j_{diode}} = \frac{j_{rec}}{j_{non\text{-}rec} + j_{rec}}$$

$$= \frac{1}{1 + \dfrac{j_{non\text{-}rec}}{j_{rec}}}$$

- With $j_{non\text{-}rec}$ (assuming that the electron and hole contributions and parameters are equal) given by the "simple" diode equation as

$$j_{non\text{-}rec} = \frac{2 \cdot e \cdot L \cdot n_i^2}{\tau \cdot N_{Dop}} \cdot \left(\exp\frac{e \cdot U}{kT} - 1\right)$$

  - we obtain for η_{cu} (neglecting the **–1** after the exponential)

$$\eta_{cu} = \frac{1}{1 + \frac{4 \cdot L \cdot n_i}{d \cdot N_{Dop}} \cdot \exp \frac{eU}{2kT}}$$

- η_{cu} thus decreases exponentially with the applied voltage and it would not make sense to include this effect in some averaged η_{qu}.

Why are we looking at radiation only from some confined part of the device, i.e., from the *recombination zone* , and not at the total volume, which demanded a finer look at the efficiencies? There are *practical* reasons, e.g.:

- If we consider a semiconductor *Laser* , only the radiation inside the "*resonator*" counts – everything outside of this specific recombination volume is of little interest.
- If we look at a light emitting diode – a ***LED*** – made of **GaP** doped with **N** (in addition to the normal doping) to produce the isolectronic impurities needed to bind the excitons responsible for the radiative recombination channel, it *only* radiates from the ***p**-side* because *only* electrons become primarily bound to the isoelectronic impurity and then attract a hole. In other words, only the electron part of the injected current will contribute to radiation.
- We must confine light production to areas close to the surface as shown in the next subchapter.
- Looking ahead we will learn that many optoelectronic devices are extremely complicated heterostructures which, for several reasons, need a precise definition of the *recombination volume*.
- To optimize the current efficiency then obviously means to maximize the flow of carriers into this volume, and minimize the flow out of it.