Optoelectronics

Key notes

5/ Light sources types

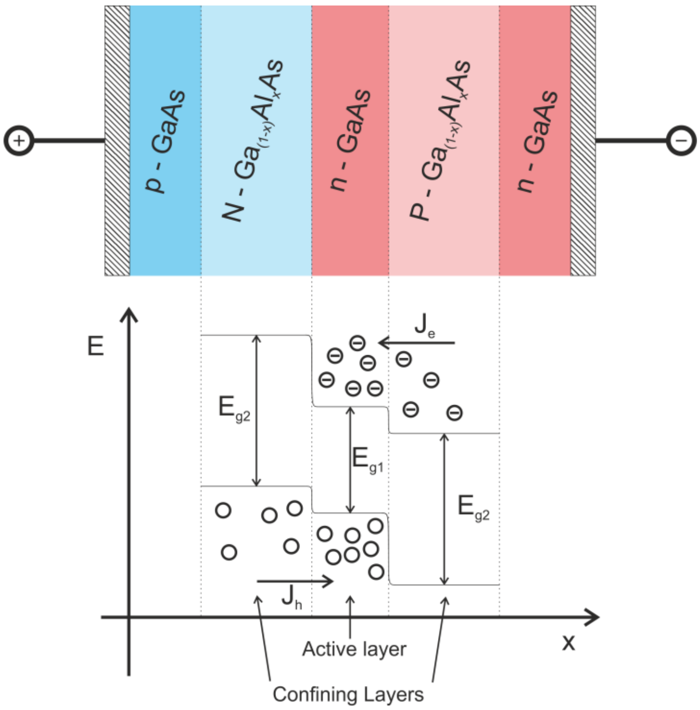
1. The heterojunction

As seen in the chapter before, the efficiency of a LED is highly inefficient for the simplest case, the p-n junction. These problems are mainly caused by:

- The re-absorption of the light by the semiconductor
- The lack of control over the size of the depletion region
- The lack of efficiency in creation and recombination of carriers.
- The null control over the wavelengths emitted (tangled to the structure of the semi-conductor

These four problems are actually achieved just by changing the internal structuration of the LED into a junction that is no longer homogenous. In the previous chapter we were always talking about a semiconductor made entirely by the same matrix (GaAs, for example) that was modified introducing some impurities (homojunction). Nevertheless, we can design a system that involves two different semiconductors and create a more efficient device. These LEDs that involves more than 2 semiconductors are called heterojunctions.

The principle of a hetero junction is to benefit by the fact that both semiconductors used have different band gaps. Let take as an example two arsenics $E_g(GaAs) = 1.43\ eV$ and $E_g(AlAs) = 2.16\ eV$. If we create an alloy of these two compounds, $Ga_{(1-x)}Al_xAs$ we will obtain a band gap ranging between both values as function of x (in a good approximation). Alternating the original semiconductor $GaAs$ and the alloy $Ga_{(1-x)}Al_xAs$ in layers with different impurities we can create an heterojunction as shown in the figure.



The regions $p - GaAs$ and $P - Ga_{(1-x)}Al_xAs$ are p-type, commonly with similar impurity concentrations, and $n - GaAs$ and $N - Ga_{(1-x)}Al_xAs$ are n-type. The main purpose of the N and P regions is to create a potential wall or barrier that prevents the carriers from going further into the semiconductor. As the energy gaps are higher there, these regions act as confinement layers increasing drastically the number of carriers (of both types) in the centre region. As the concentration of both is very high and they cannot move any deeper, the carriers will recombinate there. This intermediate region is called the active layer because the majority of the recombinations will take place in it.

The heterojunction is very popular because its simple modification in the internal structure helps improving the problems afore mentioned.

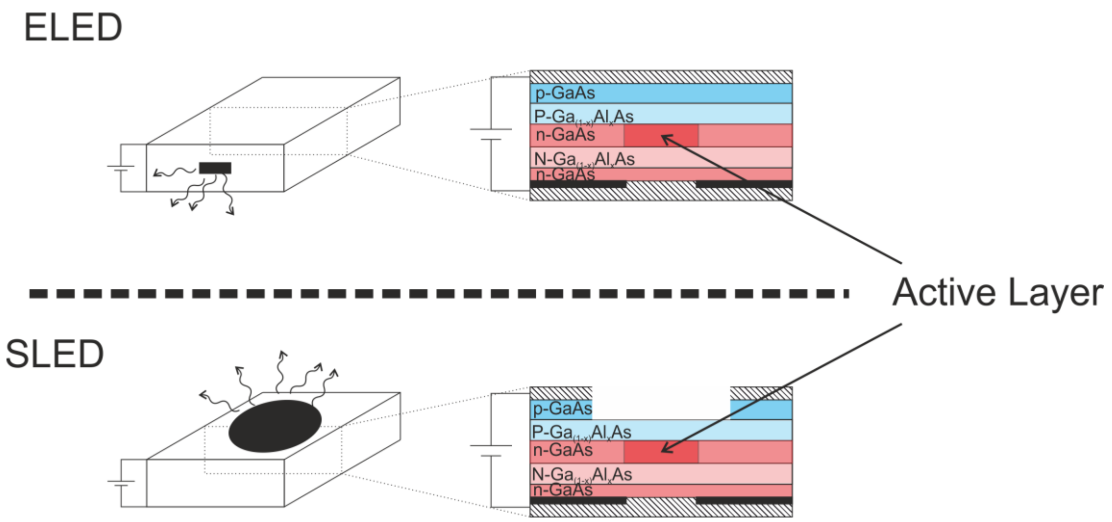
- Now it is possible to control the thickness of the active layer (in contraposition with the depletion layer)
- There is no huge reabsorption in the semiconductor, the N and P layers have higher bandgaps so they are transparent to the photons emitted in the active layer.
- As the carriers are confined in a small region with high concentrations, it increases the efficiency of the recombination process.
- It is even possible to control the wavelength of the emission if the active layer is also an alloy.

2. LED designs, incoherent

In addition to the internal layered structure of the heterojunction, additional improvements from the basics model can be done in order to increase the efficiency. Summarizing there are 3 types of popular LED designs:

- Surface LEDs (SLEDs), incoherent
- Edge LEDs (ELEDs), incoherent
- Injection laser diodes (ILDs), coherent

In the first two cases the light is collected in different ways so the efficiency varies strongly on current while the third design is almost equal to an ELED but sustained by stimulated emission. Let's have a quick review on them.



SLED. In this case the light is collected from the top surface thanks to a hole in one of the metallic contacts. This scenario allows to have a good ratio current-optical power for lower currents and it is commonly used in illumination systems. Using an insulator as in the image we can obtain higher efficiencies at cost of stronger thermal effects (the area is smaller).

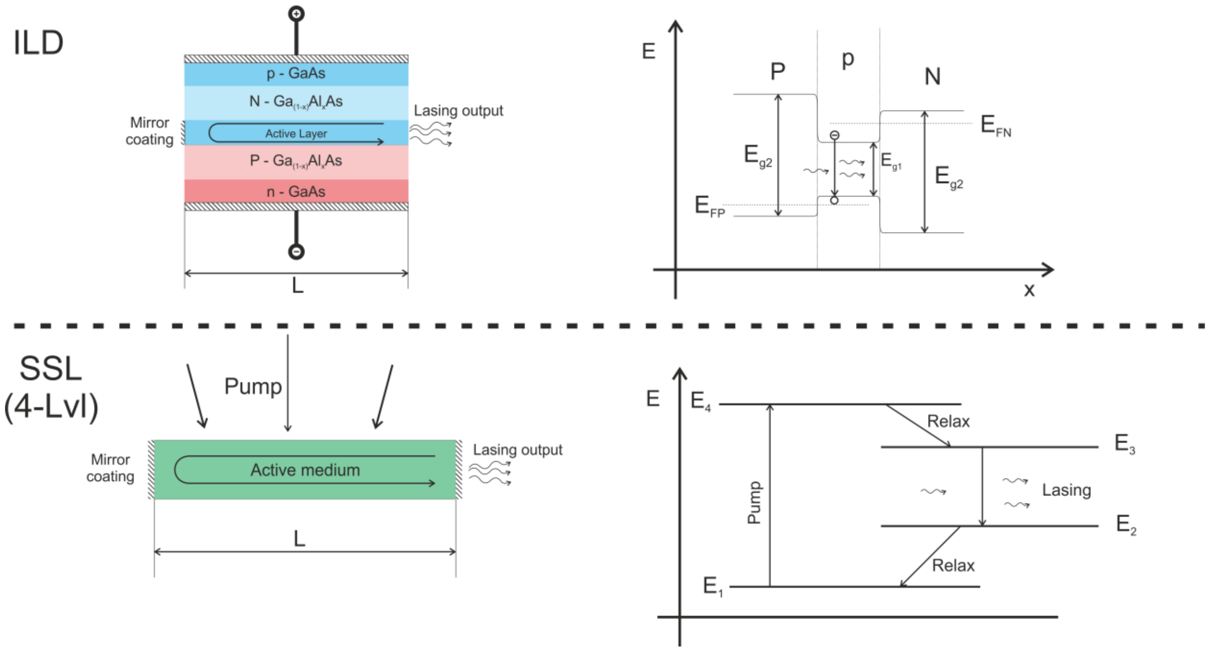
ELED. The light is collected at the end of the layer structure. It benefits from having a linear response to power in a wide regime and low divergence of the beam in the layer structure dimension. The small divergence and their dimensions are optimal for coupling the output to optical fibres.

3. LED designs, coherent (ILD)

The third type of LED design use almost the same structure as the ELEDs but the main difference is how the light emitted is generated. In the first two cases, spontaneous emission is the main procedure to generate photons, two carriers recombinate and generate a photon with a given energy determined by the starting and final energy levels of the electron. We can describe the lifetime of a carrier as function of the rates of recombination

$$\tau = \frac{n}{R_{RR} + R_{NR}} = \frac{n}{(R_{sp} + R_{st}) + R_{NR}}$$

Where R_{RR} and R_{NR} are the ratios of recombination for radiative and non-radiative reactions where the contribution for the first can be decomposed into spontaneous and stimulated emission $R_{RR} = R_{sp} + R_{st}$. In previous sections we have considered that $R_{RR} \approx R_{st}$, but now that the power and the carrier densities are higher the stimulated emission is no longer negligible. In fact, when the optical power increases in the active layer and the energy gaps have been properly determined, the rate of recombination due to stimulated emission becomes dominant and we can talk about the last category, injection laser diodes (ILD).



As it can be seen in the figure, the typical structure is the same as the ELED but the conditions for its operation are different (higher V values and doping concentrations). The condition for the energy levels and the stimulated emission are similar to those of a 4-level solid state laser (SSL), where now the emitted light is that corresponding as the energy gap of the active layer (E_{g1}) and the population inversion is between the fermi levels from both P and N regions. In this case, the pump is either electrical or optical if the pump light has an energy equal or greater than the bandgap in the confining layer

Similar to the gain in a solid state laser cavity, we can define the gain coefficient

$$G = R_1 R_2 e^{2(g-\alpha_{eff})L}$$

Where $R_{1/2}$ are the edges' reflectivity, g is the gain coeffient, α_{eff} is effective absorption (absorption + losses) and L the length of the cavity. In order to produce the lasing effect, this gain must be over 1, so the gain coefficient threshold g_{th} so the lasing effect happens is:

$$g_{th} = \alpha_{eff} + \frac{1}{2L}\ln\left(\frac{1}{R_1 R_2}\right)$$

Which determines the external quantum efficiency of the ILDs

$$\eta_{ext} = \frac{(g_{th} - \alpha_{eff})}{g_{th}}$$

$$\eta = \eta_{int}\eta_{ext} = \eta_{int}\frac{(g_{th} - \alpha_{eff})}{g_{th}}$$

Finally, it is important to note that not all the wavelengths emitted by the active layer will be amplified as the phase matching condition must be fulfilled ($\Delta\phi = m2\pi$, phase during a round trip). Which means that only the wavelengths supported by the cavity length and emitted by the diode will amplify.

$$\nu = \frac{mc}{2nL}$$

$$\Delta\nu = \frac{c}{2nL}$$

Where ν and $\Delta\nu$ are the frequencies supported and the separation between them, m is a positive integer, c the speed of light and n the refractive index of the active layer.

Recommended bibliography:

- Anil K. Maini, << Lasers and Optoelectronics: Fundamentals, Devices and Applications>>, 2013 John Wiley and Sons Ltd, ISBN: 978-1-118-45887-7, Chapter (5, 9, 10)
- John P. Dakin and Robert G.W. Brown, << Handbook of Optoelectronics, Second Edition: Concepts, Devices and Techniques – Volume One>>, 2018 Taylor & Francis Group, ISBN: 978-1-4822-4178-5, Chapter (10,11,12,19)