A Brief Introduction to Laser Diodes

This definitely won't do for a course, but if you're not familiar with laser diodes, this might be a good place to start. I am deliberately light on the equations and details in the hope that it will be easier to grasp an understanding of this stuff. If you're going to specialize further, then you will need to dig further and get the details!

Diodes

First, let's just start with plain diodes. A diode is simply made from 2 pieces of semiconductor material (or likely, one piece with 2 different regions). These are usually called the n doped region and the p doped region. Hence, a diode is commonly simply referred to as a pn junction.

Why? Because, normally a piece of semiconductor (e.g. Silicon) usually doesn't have any free electrons, so it is a poor conductor (hence semiconductor). It is not as bad as a pure insulator, nor as good as a good conductor, such as metals. In order to provide free electrons, what you do is "dope" the semiconductor. By doping, you mix in some impurities into the semiconductor (in this case, Silicon). Just have a look at the table of elements and go on either side of Silicon, say Phosphorous (P) and Boron (B), for example. The extra P atoms try to fit into the Silicon lattice, but oops! it's got an extra electron! So in order to fit in, it manages to "give up" one to be a somewhat free electron. Similarly for the B, it tries to fit into the Silicon as well, but it's missing an electron compared to its neighbours, so it will have an extra "hole", which it will try to fill in, so the hole can have the possibility of getting shuffled around. You can't put in too much, of course, or else it isn't Silicon any longer and the whole lattice gets messed up...

So, let's go inside and take a look at what happens. In an intrinsic (un-doped) piece of semiconductor, it has a certain bandgap between the valence and conduction band, and Fermi energy level which usually lies in between. This is described by the following equation:

$$E_f = \frac{E_g}{2} + \frac{3}{4} k_B T \ln\left(\frac{m_h^*}{m_e^*} \right)$$

[Equation 1]

where:

E_g = *bandgap energy*
k_B = *Boltzmann constant*
T = *temperature*
m_h^* = *effective hole mass*
m_e^* = *effective electron mass*

(Note that the effective mass isn't the same as the actual mass, even assuming that holes have mass!).

The bandgap diagram is boring. Flat line kind of boring, so we'll not bother looking at that.

Now, when we add dopants, we change things a bit, and in particular, we refer to the Fermi level energy (or probably more appropriately, the quasi-Fermi level, but we'll use it the same way here). The quasi-Fermi level in a doped material can be described by:

$$E_{fn} = E_f + kT \ln\left(\frac{n}{n_i} \right)$$

[Equation 2]

$$E_{fp} = E_f - kT \ln\left(\frac{p}{n_i} \right)$$

[Equation 3]

where:

E_{fn} = *quasi-Fermi level in the n-doped material*
E_{fp} = *quasi-Fermi level in the p-doped material*
n = *carrier concentration of electrons*
p = *carrier concentration of holes*
n_i = *intrinsic carrier concentration*

(Note: n and p are usually equal to the doping concentration).

You can see from the equations then that the Fermi level for the n region goes up, and the p region goes down relative to intrinsic material. Now, when you join the two regions, the quasi-Fermi level still has to line up somehow. It can't move. So what happens then is the valence and conduction band, while fixed relative to the Fermi level in their own region, shifts to compensate. This we show in the diagram below.

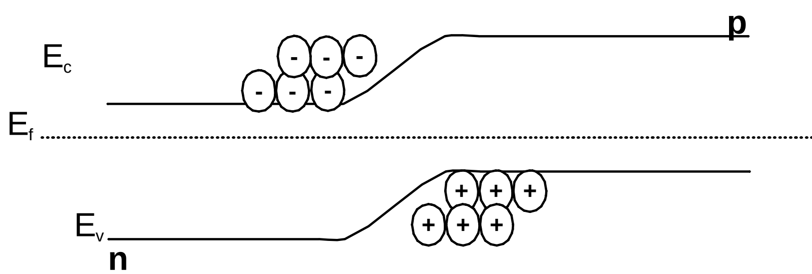

Figure 1: Energy band diagram for pn junction

Pretty cool, eh? But nothing happens yet. Come on, you can't have currents flowing from nothing. Mother Nature adjusts everything accordingly so that there isn't any *net* current flow with a piece of pn junction just sitting around. But, we can do something about it. If we apply a positive voltage to p with respect to n (that is, p only has to be of a higher voltage than n), this is called forward bias. What you can imagine happening is that the band diagram gets "squished", the p and n regions get closer together (vertically).

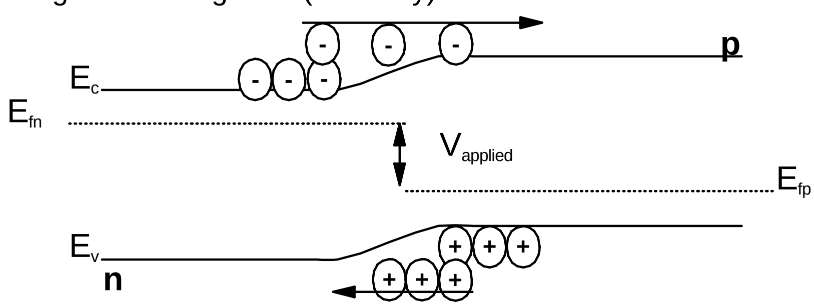

Figure 2: Energy band diagram for pn junction under forward bias

Now something interesting happens. All of a sudden the excess electrons in the n region see a lower barrier to the p side, and a bunch of them go tumbling over. And similarly for the holes. And that is current flow!

That in itself isn't that interesting, I mean you could do that with a piece of wire. But consider the opposite case, reverse-bias, where n is of a higher voltage than p. Then instead of getting closer together, the n bands shift lower and the p bands shift higher. There is now a bigger barrier for the excess electrons on the n side to climb over if they want to get over to the p side. There is practically no current flow. Now that becomes more interesting, because you have a junction which effectively conducts one way, but not the other.

Light Emitting Diodes

We'll talk about regular Light Emitting Diodes (LED's) first, as laser diodes are merely special case of LED's.

Now in the case of a light emitting diode, what you want is the carriers in the middle region to linger long enough to recombine and emit light. What is happening is a hole becomes available, and the electron says "hey, I can go to a lower energy!", which it does, if it has time, and emits energy equivalent to the bandgap E_g.

That sounds pretty simple, but there are a few problems to overcome, which all fall under the category of **internal quantum efficiency**. There are some processes which are not non light emitting processes. Maybe there's a "shallow impurity state", (i.e. not at E_v), then the electron gets recombined, but less energy comes out, and not in the wavelength of interest. Or there are deep recombination centers, which will also cause a non-radiative recombination.

We can increase our chances of getting radiative efficiency by increasing p-doping generally, but only up to a point. The problem is that introducing more dopants also increases defects, which increase the other recombination factors as well.

Now, once you've made light, you need to get it out. These problems are under the area of **external quantum efficiency**. Some of the light may get re-absorbed, for example. So what to do? One trick is to make a heterostructure. We have a p material right next to our main photon generating p material, but make it different! If it has a larger E_g, then the photons initially generated won't get absorbed by the secondary material. One common material used is p-doped AlGaAs.

And also secondly, total internal reflection due to refractive index mismatch can be a problem. In GaAs, the small cone of from which light can escape to air is only about 10-15°. One solution to this problem has been to insert a secondary material (such as some plastic) with an intermediate index of refraction, and make that outer surface spherical. This greatly enhances the amount of light that can escape.

Laser Diodes

Now for lasers, just getting light out isn't enough, you need some serious doping to get the population inversion that you need. You need both sides to be degenerate so that the Fermi level is within the E_c and E_v. Basically, you just want to make sure all carriers are in the same energy state, so that all your photon generating transitions are consistent.

Side emitting lasers

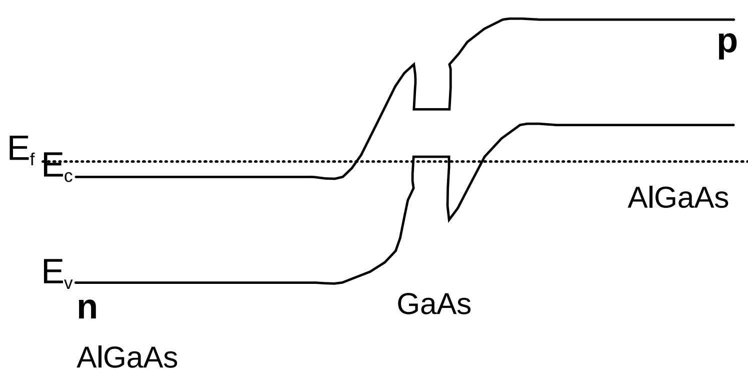

Figure 3: Energy band diagram for laser diode

Figure 3 shows a energy band diagram for a simple edge-emitting laser. In the simplest case it's a p-i-n diode (where i is for intrinsic), an it's an improvement on a regular p-n diode, as an energy well is desirable for trapping the carriers so that they have a chance to radiatively recombine. This heterostructure is the de-facto standard used as the basis for designing all edge emitting diode lasers. Figure 4 shows a simple diagram of how this laser is actually implemented.

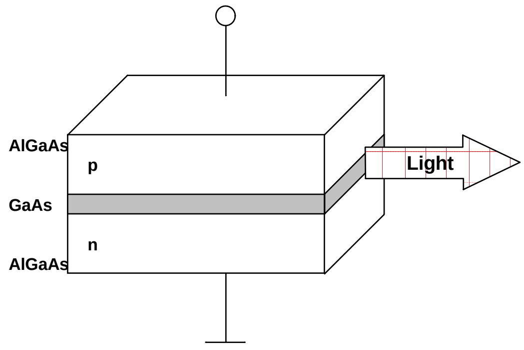

Figure 4: Simple edge emitting diode laser

Usually the Fabry-Perot laser cavity has faces (100) so that the two "mirrors" are nicely parallel. In the simple case, just the interface between GaAs and air can provide the reflectivity needed. The other sides which don't participate in the lasing can have roughened sides, or some other scheme to prevent photon emission.

Since we actually get leakage out the "back" face of the laser as well, it is commonly used as part of a simple monitor circuit to verify laser operation (e.g. backed by a photo-diode or some other scheme).

Now in practice, there are many tricks to get efficient lasing and optimize various other desirable parameters. These are usually trade secrets...

Vertical Cavity Surface Emitting Lasers

Now for Vertical Cavity Surface Emitting Lasers (VCSEL), things get trickier. The idea is that the laser cavity is no longer in the horizontal plane, but is instead, vertical. The reasons that this is advantageous are due to the many issues related to fabrication of semiconductor devices. At the current time, fabrication is accomplished by laying different layers of material on top of another, and this is typically done on very large "wafers". For example, 100's of computer chips are fabricated at once on 300mm wafers, which are then diced up into individual square die after the fabrication is complete. Having active structures on the side of a device makes it difficult to fabricate, especially in volume.

It is not possible at this time to simply rotate the side emitting laser structure because we are capable of providing excellent thickness and planarity control in the vertical direction, but not in the horizontal direction. In the vertical direction, very uniform layers can be grown, which can subsequently be polished (e.g. polishing via wet slurry) to a near perfect flatness, and to almost any thickness desired. In the horizontal direction, very thin structures are extremely difficult to manufacture accurately due to material filling problems and the resolution of the structures possible when using light to expose photo-resist.

So, the idea behind VCSEL's is fairly simple, just build up a vertical laser. That's great, but consider the edge-emitting laser and how it is fabricated. Suppose the laser cavity is now vertical. How does one inject carriers into the active region, and once there, how do you have a transparent cavity to extract the photons?

In practice, the actual fabrication is very complex. A typical VCSEL uses many layers, not only to build up the active regions required, but also to fabricate the distributed Bragg reflector (DBR) structures that are used as the lens and mirrors. One design might go something like this starting from the top layer:

- Coat with polyimide (mechanic strength and UV protection), something like $C_{22}H_{10}O_4N_2$.
- Au/Zn/Au p-electrode
- p-type $Al_{0.7}Ga_{0.3}As$/GaAs DBR (21 layers)
- AlAs oxide aperture for optical confinement (80nm)
- The active region consisting of 3 layers of alternating GaInAs (8nm) / GaAs (10nm) to define 3 quantum wells (GaAs used as the barrier)
- AlAs oxide aperture for optical confinement (80nm)
- n-type $Al_{0.7}Ga_{0.3}As$/GaAs DBR (21 layers)
- GaAs substrate
- Bottom AuGe/Au n-electrode

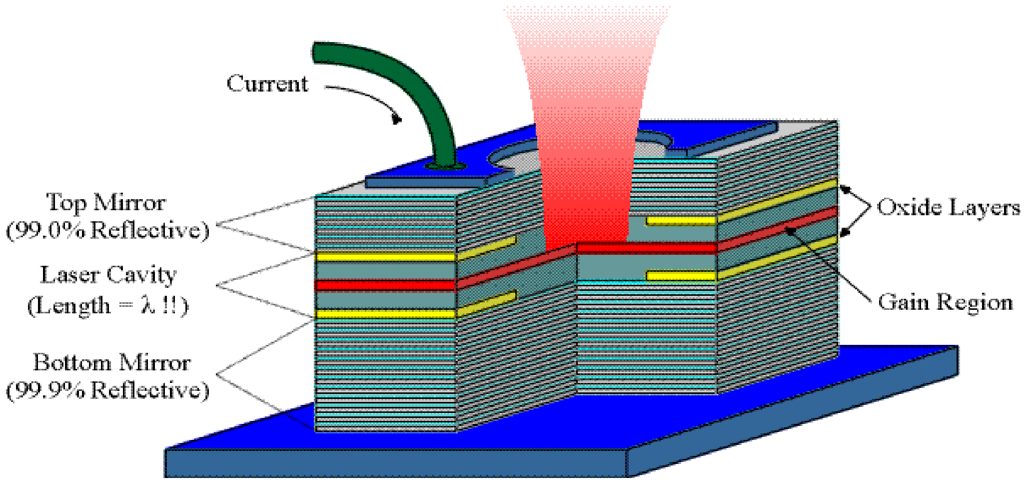

Figure 5: Sample VCSEL

Quantum Wire/Quantum Dot Lasers

Why do we want quantum lasers? Well consider this, in order for lasing to occur, we need a certain minimum current. This current can be described by:

$$I_L = \left(\frac{qN_{inj}d}{\tau_r}\right)WL$$

[Equation 4]

where:

q = electron charge
N_{inj} = injected carrier density
d = active layer thickness
τ_r = carrier lifetime
W = laser cavity width
L = laser cavity length

Lasers aren't terribly efficient, due to non-radiative recombination and various other losses. By inspection of the above equation, one can see that to reduce the current required (and hence, increase efficiency), one strategy is to reduce the cavity size (either width, length or layer thickness, or all three!). That's why quantum lasers are of interest.

Laser Diodes in NMR Spectroscopy

Why? Because we can use a polarized laser light to induce more spin in a material than would otherwise be possible with just magnetic fields. At the current time, in order to use this effect, we have to setup an external laser source. Not only is this expensive, but it isn't as robust and is more troublesome to setup and has some technical problems when one wants to perform measurements at very low temperatures.

By using a diode laser, we could fabricate a array of laser diodes and have that directly in contact with the sample we want to measure. It is potentially much cheaper and more convenient.

So, what do we want in a laser diode? Well, for starters, we need to have a stable, polarized source of laser light. Sounds easy, and it should be, but this has serious implications for the choice of laser diodes. Side emission type lasers, by their physical configuration, nicely favour one mode of polarization that is predictable and stable. The disadvantages are the ones listed for VCSEL vs. side emitters, in terms of efficiency, form factor and manufacturing.

On the other hand, while VCSEL's exhibit many desirable properties, among them a nicely circular, low divergent beam pattern. However, the same symmetry gives us a problem, in which the polarization is not typically predictable, and may not even be stable. The reasons behind this are not well understood at the current time. There is some research to indicate that particular circuit geometries or even the switch from a (100) GaAs substrate to (311) GaAs substrate for MBE grown VCSEL's can stabilize the polarization.

Quantum well/quantum dot lasers are really cool, but the advantages they offer don't concern our particular application, where all we want is nicely polarized coherent light. Certainly they are very troublesome to design and fabricate at the current time. However, we should note that one of the methods that have been attempted in the past at making quantum wire lasers involve using a very strong magnetic field to confine carriers on regular diode lasers. This is obviously not feasible for mass production type designs, and it seems very little work has gone into this. If we are to utilize regular side-emission laser diodes, we will most likely have to do some sort of minimal characterization of the laser performance. If we have the data, it might be worthwhile to publish some results as well, as it isn't typical for most researchers working on laser diodes to have access to such magnetic fields. Previous results have indicated possible reduced temperature sensitivity of the threshold current.

The same lack of requirements can also work in our advantage. In fact, we don't even necessarily need to extract any photons because we don't want the light. We only want it to induce greater spin polarization, and if this can be transferred from the photons in the active region to some of the bulk material which makes up the laser and into the biological sample, that's all we require. Much of the complexity (for example in the DBR) is required to get proper lasing and to efficiently extract the photons.

Glossary

Term	*Definition*
CMP	Chemical Mechanical Polishing
CVD	Chemical Vapour Deposition
DBR	Distributed Bragg Reflector
LED	Light Emitting Diode
MBE	Molecular Beam Epitaxy
NMR	Nuclear Magnetic Resonance
VCSEL	Vertical Cavity Surface Emitting Laser

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