9. Optoelectronics

9.1 General Concerns

9.1.1 Semiconductors and Light

Basic Questions

Optoelectronics here means the coupling of *optics*, i.e. *light* (including all relevant wavelengths from the far infrared to the deep ultraviolet) and *electronics*, and that this is somehow done with semiconductors. We have two basic possibilities.

- **1.** The input is light, the output is an electrical signal or electrical power.
  2. The input is electrical power and the output is light
- If we go for less orthodox definitions, we may also consider
  3. Electrical input switches light on or off or, more generally, modulates light.

Let's look at a few examples:

- For the first point we have solar cells, if you like, although few people would count then among optoelectronics proper. The paradigm for this field is the **optical sensor**, sitting, e.g., at the end of a fibre optics cable and converting the signal coming in in the form of light being on or off to electrical signals. A more ubiquitous product example is the "***CCD***" chip in your digital **8** Megapixel camera, that contains no less then **8 Mio** optical sensors in a matrix.
- For the second point we have *two* paradigmatic products. ***LED's*** - **light emitting diodes** and ***LASER*** **diodes**. Both devices are closely related technologically, but quite a bit apart from their working principles.
- The third example could include **flat panel displays** in the form of "***LCD's***" and all the light manipulating **MEMS** devices we already considered in the MEMS context. Nobody would list those devices under optoelectronics proper, but we do have a connection between light and semiconductors.

As far as this lecture course is concerned, we can just touch upon the basic principles of **LED's** and Lasers. So let's look at a few general points in the context of producing light in a semiconductor by running a current through it. This brings us to the first major point:

1. Generating light takes *power* - current I times voltage U.

- Just having almost powerless voltage swings, which are (almost) all you need for processing information, will not suffice. There is some energy $h \cdot \nu$ contained in the light generated that we want to flow *out* of the system, and thus some energy $I \cdot U \cdot t$ must flow *into* the system.
- That means we always have some **efficiency** η (measured in **%**) associated with the process of light generation; and η, as always, should be as large as possible. In fact, with **LED's** we can achieve rather large efficiencies **> 50 %** (compare that to to a light bulb with ≈ **7 %**!), if everything is done just right.

2. LED's generate light with just one wavelength λ (of course with some $\pm\Delta\lambda$).

- The **wavelength** λ (or the frequency ν) of the light generated is more or less determined by the band gap. We already looked at the possibilities we have for **bandgap-engineering** in our "master diagram"; the basic relation is

$$\lambda = \frac{c}{\nu} = \frac{h \cdot c}{h \cdot \nu} = \frac{h \cdot c_0}{n \cdot E_g}$$

  with E_g=band gap energy, and c=speed of light in the medium the light is propagating, i.e. $c=c_0/n$ with c_0=speed of light in vacuum, and n=index of refraction $=(\epsilon_r)^{1/2}$; ϵ_r is the relative dielectric constant of the material.
- There - you have elementary optics coming in as you should have suspected when the "*opto*"electronics came up. In other words, the **dielectric constant** and with it the **index of refraction** of our semiconductors enters the game here, a property we have hardly noticed so far.
- Most semiconductors, actually, have a rather large index of refraction; some values are given in the table below. In case you wonder why materials that are not transparent to light should have an index of refraction, keep in mind

  1. All semiconductors are perfectly transparent to light with $h \cdot \nu < E_g$; so at least for small enough wavelengths an index of refraction makes perfect sense.
  2. In that part of optoelectronics where we want to produce light, we must work with wavelengths where the semiconductor is at least semitransparent. Otherwise no light could possible come out of the material.
  3. If we cool *any* semiconductor down to a sufficiently small temperature, it will be a good insulator for which we can easily define a dielectric constant and thus an index of refraction.
- In fact, looking ahead to somewhat more advanced material science, everything contained in notions like *electric conductivity*, *dielectric constant*, *index of refraction*, or *absorption coefficient* are just special aspects of a so-called (complex) **dielectric function**, which is nothing but the (complex) dielectric "constant" as a function of frequency; more to that in the link.

3. A third point of general interest is the *absolute intensity*, or even more specific, *the intensity density* we can produce. In other words, when we generate a certain "amount" of light as given by energy in times efficiency, from what kind of volume is it coming from.

- From a "point source" as we like it (in text books) for doing optics with lenses; from some finite volume like in a real light bulb, from some elongated structure like in a fluorescent tube, or from a large area like - ???.
- Well, with "normal" light sources you have a problem if you need two-dimensional light sources. You just can't throw a light switch and have a whole wall of your room start glowing uniformly - until you go for (future) **LED's**, that is.
- Whatever, we have an important point here that we need to address if we want to use **LED's** for making light.

If we take points **1 - 3** and remember that a photon in an **LED** will only be produced if an electron and a hole recombine in a process that transfers their energy to a photon (and not to the lattice or to something else) we have our task cut out:

1. Recombine as many electrons and holes as you need per second (⇒ *current*)
2. for the amount of light you want to produce (⇒ *intensity*)
3. with as many recombination events as possible producing light (⇒ *efficiency*)
4. in a defined volume (⇒ *intensity density*)
5. *and* get the light produced out of the semiconductor (⇒ *efficiency once more*).

- In simple and straight terms, we need to consider how we can handle *massive recombination* in a given volume. We need to do this for a number of different semiconductors because we need different wavelengths.
- This is new! So far we tried to either avoid recombination (e.g. in solar cells) or to ignore it (e.g. in the simple standard version of the diode equation). Now recombination is in the focus of what we need to optimize.
- What is also new to some extent is that we are now using (electrical) **power=*UI***. It you want to produce a lot of light (=energy), you must provide power. You can't get much light out of **1 W** light bulb and you can't get much light out of just a **1 W LED** either. This is new to some extent because in microelectronics (=communication and signal processing) we avoided power as much as we could - we had voltage swings, but no current if possible.

Material Issues

Color	Wavelength (nm)	Typical Semiconductor
Infrared	**880**	**GaAlAs/GaAs**
Red	**660 - 633**	**GaAlAs/GaAs**
Orange to **Yellow**	**612 - 585**	**AlGaInP** **GaAsP/GaP** **GaAsP/GaP**
Green	**555**	**GaP** **AlInGaP**
Blue to **Ultraviolet**	**470 - 395**	**AlInGaPNGaN/SiC** **GaN/SiC** **InGaN/SiC**

As already pointed out above, we need several suitable semiconductors to cover all aspects of optoelectronics.

- It also became clear that we have to look at more properties than we did so far : For example, *dielectric constants* and *recombination mechanisms* are now prime parameters we must consider.
- The value of the band gap, too, is now of *prime* importance (In contrast, we wouldn't have cared much about the *precise* value of the bandgap for **Si** technologies!).

Besides appreciating the material overview given in the table at the right, let's look a bit closer at major semiconductors and their properties in detail: The same table but with more entries concerning properties we have not yet encountered can be found in the link.

- Interesting points that can be found in this table are
  - *Indirect* semiconductors like **GaP** are listed!
  - A *strange recombination* mechanism ("exciton - band") is listed
  - A *strange semiconductor* (**$In_{0,53}Ga_{0,47}As$**) is listed

Here is a table with a lot (but not all by far) interesting properties of some semiconductors:

Properties	**Si**	**Ge**	**GaAs**	**InP**	**InSb**	**$In_{0,53}Ga_{0,47}As$**	**GaP**	**GaN**	**SiC**	**Diamond**	**Remarks**
Crystal											
Unit weight [mol]	29,09		144,63	145,79		168,545					
Density [g/cm^3]	2,33		5,32	5,49		5,49			3.166 (cubic) 3.211 (hex)	3,51	

Crystal structure	Diamond	Diamond	Sphalerite	Sphalerite	Sphalerite	Sphalerite			Many variants cubic, hex, rhombohedral	Diamond	
Lattice constant [nm]	0,5431	0,565	0,565	0,587	0,648	0,5867			a=0,30 c many values		
Transport properties											
Band gap [eV]	1,12	0,66	1,42	1,35	0,17	0,75	2,26		2.39 - 3.26	5.47	
Type	Indirect	Indirect	Direct	direct		direct	indirect		indirect		
Effective e^- mass [m^*/m_0]	0,98								0,24 - 0,7		
Effective h^+ mass [m^*/m_0] light heavy	0,16 0,49		0,082 0,45	0,12 0,56	7,3	0,051 0,50			0.9		
N_{eff} in C [$10^{18}cm^{-3}$]	28 (32)	10,4	0,47	0,54	0,042	0,21					
N_{eff} in V [$10^{18}cm^{-3}$]	10 (18)	6	7	2,9		7,4					
n_i [$10^6 cm^{-3}$]	6 600 13.000		2,2	5,7		63 000					
Mobility (undoped) [cm^2/Vs] μ_n μ_h	1 500 450	1 900 3 900	8500 450	5 000 200	80 000 1 250	14 000 400	300 150		500 - 1 000 20 - 50	200 - 2 200 1.800 - 2 100	
Lifetime (general) [µs]	2500		0,01	0,005		0,02					
Mecha-nism of lumines-cence	None		band-band	band-band		band-band	exciton-band if doped				
Dielectric properties											
Dielectric constant	11,9	16	13,1	12,4	17,7	13,7	11,1		9.7 - 10	5.5	
Break through field strength [kV/cm]	300		350	400		100					
Specific intrinsic resistance [MΩcm]	0,2		310	11		0,0008					
Electron affinity [eV]	4,0	4,05	4,07	4,4	4,59	4,63	4,3				
Thermal Properties											
Expansion coefficient [10^{-6} $^oC^{-1}$]	2,6		6,86	4,75		5,66	5,3			1	
Therm. conductivity [W/cmK]	1,5		0,45	0,68		0,05			5.0	22	Cu: 4.01
Specific heat [J/g^{o}C]	0,7		0,35	0,31		0,29			0.671	0.428	Cu: 0.38

Melting point [ºC]	1 412	937	1 238	1 062	527	970					

- **Si**, **Ge** and diamond are included as references; if there are several numbers, they are from different sources. We find expected properties, but also, perhaps, some unexpected ones:
  - *Dielectric constants* are relatively large even at the very high optical frequencies. That means we have also large *indexes of refraction* $n=(\epsilon)^{1/2}$.
  - **Thermal conductivity** can be rather large (**SiC** and diamond!). That's good because we have to get a lot of heat out of our optoelectronic "power" devices.
  - There is at least one recombination mechanism not mentioned before: *Exciton - band* recombination.
- This tells us that we now need to look a bit more closely at radiant *recombination*, the key to light generation.

Radiant and Non-radiant Recombination

- Let's start from the typical situation of a working **LED** or **Laser**. 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***.
  - What they *want* to do is to recombine because that would be the right step towards equilibrium.
  - What they are going to do depends on the conditions. They must be "just right" otherwise recombination will not take place. Essentially three conditions must be met:
    1. The electron and the hole must be in the *same place* at the *same time*. The probability for that happening is certainly proportional to the respective concentrations n_e and n_h.
    2. We must *preserve energy*. The energy released by the recombination (=E_g) must appear somewhere else; in the world of quantum mechanics always in some *particle* like a freshly generated photon.
    3. We must conserve (crystal) momentum.
  - In direct semiconductors we know we don't have to worry about point **2** and **3**. Whenever boy meets girl in this case, things can happen and they can recombine, emitting a photon. We have what we now will call **direct recombination**.
- This is still true and will remain true. But now we have to look a bit more closely and realize that other things beside the direct recombination *might* happen too.
  - For instance, 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 is exactly how recombination happens with the help of defects in indirect semiconductors. There is no reason in the world why this must not happen in direct semiconductors, too. It does, and the problem is that you can meet conditions **2.** and **3.** from above without emitting a photon, The third partner to the process - the defect - takes care of energy and momentum conservation.
- We thus have recombination via defects as a second **recombination channel**, to use the proper term. We don't like this recombination channel because it takes electrons and holes out of circulation without producing light, and therefore decreases the efficiency of our **LED**.
- Now we must make a leap in imagination. Third partners to the recombination process, that much is clear, may somehow influence what happens. The question is thus: What kind of third partners besides defects do we find in semiconductors and what, exactly, are they doing to recombination?
  - A simple first answer is: Electrons in the conduction band. What happens is that an electron meets an attractive hole, recombines, and the energy released goes right to a second electron that happens to be close by. This process is called "**Auger recombination**" and we don't like it because it does not produce light.
  - A not-so-simple-answer is: Bound **excitons**! So an electron gets very close to nice hole, but can't recombine because they are in an indirect semiconductor, and their momentums just don't fit. However, there is still some attraction (Coulomb attraction) as long as they stay real close because they have opposite charges. So they form a bound electron-hole pair, encircling each other (always exactly opposite momentum!), and run about as a pair called "*exciton*" that would like to do it but can't quite without a little help from a friend. Then they encounter a friend in the form of a special defect (**N** atoms in **GaP**, for example) that traps the couple, i.e. *localizes* it in space. Great - because now Heisenbergs uncertainty relation kicks in: $\Delta x \cdot \Delta p > h$. If Δx is small, Δp, the uncertainty of the momentum p, is large. If your momentum is uncertain, what exactly needs to be preserved? Right - happy recombination, you have made it now. And don't forget to ~~use a condom~~ emit a photon while you're doing it because we still must have energy conservation!
  - Wow! We now have a somewhat strange recombination channel that produces radiation, which is good!. It is actually the only reason why the indirect semiconductor **GaP**, if "doped" with **N** to catch the excitons (in addition to the doping that produces the electrons and holes), will be a quite efficient material for green **LED's**.
  - This little excursion into more advanced semiconductor technology just serves to demonstrate that there are indeed more recombination channels than we might have thought of. Moreover, the "blabla-ons", they many so-called "**quasi-particles**" of solid state physics, often considered to be exotic curiosities with no conceivable uses, are quite useful, after all. At least some of them, including the exciton. The link will go somewhat deeper into these subjects.

- We aren't even done yet. There are even more recombination channels but what we have learned so far suffice to make the point:
  - If you want a high-efficiency **LEDs** and Lasers, you must optimize your recombination channels - and this may not be easy.