2.3 III-V Semiconductors

2.3.1 III-V Semiconductors and Optoelectronics

The Need for III-V's

- Next in importance to the elemental semiconductor **Si**, we have the **III-V compound semiconductors** obtained by combining group **III** elements (essentially **Al**, **Ga**, **In**) with group **V** elements (essentially **N**, **P** , **As**, **Sb**). This gives us **12** possible combinations; the most important ones are probably **GaAs**, **InP GaP** and **GaN**.
  - All of these **III-V** combinations crystallize either in the diamond lattice like **Si** or **Ge**, often called "**Zinc blende**" or **ZnS** structure (the term "**sphalerite** structure" is used, too), or in an hexagonal lattice known as "**wurtzite**". For your ***edification*** both structures are shown and explained in the link.
- What can **III-V**'s do that **Si** cannot do? This is an absolutely essential question for an *engineer*.
  - In your **engineer mode** (as opposed to your scientist mode) you think *exclusively* in terms of **applications** and **products**.
  - In a good first approximation, using a new material for an existing product is *only* sensible if it makes the product *better* or *cheaper* (or both). Looking at just "raw" **Si** single crystals, no other semiconductor comes even remotely close with respect to prize / performance. There are simply *no* large practically defect-free cheap wafers of other semiconductors!
  - So there must be a very compelling reason to use **III-V**'s for application that **Si** just can't hack. Obviously, this is **optoelectronics** for starters.
  - Obviously, because by now you know that **Si** has an *indirect* band gap and that means it will not **emit light**. If we want to produce **light emitting diodes** (***LED's***), we simply cannot use **Si**.
- This brings us right to the most important set of **III-V** properties: Size *and* nature of the band gap:
  - **Class Exercise:** *What would we like to have here?*
  - Let's look at what we really have - if we like it or not:

Properties	**Si**	**GaAs**	**InP**	**GaP**	**GaN**	**$In_{0,53}Ga_{0,47}As$**
Band gap [eV]	1,12	1,42	1,35	2,26	3.39	0,75
Type	Indirect	Direct	Direct	Indirect	Direct	Direct
Lattice	fcc	fcc	fcc	fcc	hex	fcc

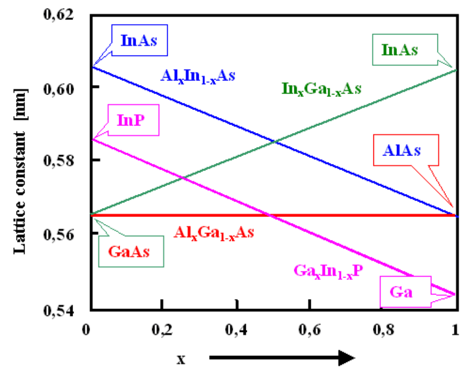
- Some questions should come up:
  - Where does that leave us with **optics** - what kind of light can we get out of these compound semiconductors? The next figure will provide the answer for this question.
  - How about **GaP**? It has an indirect band gap but is still used for making **LED**'s (just believe it)?
    Yes - there are tricks to get an indirect semiconductor to emit light. For some materials they work, for others they don't. How it is done is beyond our ken at present; things like "excitons" (one of the many quasiparticles of solid state quantum theory) "quantum wires" or "quantum dots" will be invoked. This link moves you on to a suitable module of a graduate course if you are curious.
  - Does the last column imply that we can also have mixed cases? Yes - but only for thin films
  - Is it technically important if we have wurtzite or sphalerite; how about the lattice constants? Yes and yes - this is even *extremely* important.

Ternary and Quaternary III-V's

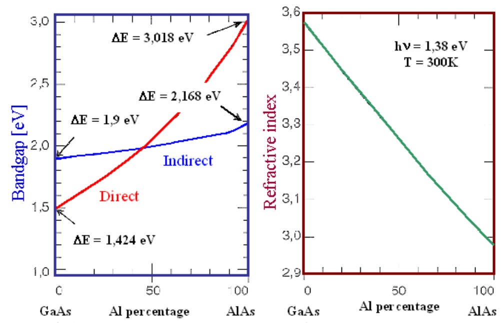
- We have **GaAs** and **GaP** - what keeps us from *mixing*, forming for example **$GaAs_xP_{1-x}$**?
  - Nothing, of course - provided that the (**ternary**) phase diagram provides for such a compound.
  - We can do even better by producing a **quaternary III-V** compound with the structure **$III_yIII_{1-y}V_xV_{1-x}$**.
- Now we have a large research program: Find out what can be done for all kinds of combinations of **III's**, **V's**, ***x*'s** and ***y*'s**.
- Fortunately we can make a few educated guesses of what might happen; and we do that for *ternary compounds* (**$III\text{-}V_xV_{1-x}$** or **$III_xIII_{1-y}V$**) to keep it easy.
  - **Lattice constant**: As long as the lattice *type* doesn't change, the lattice constant most likely will just smoothly change from one extreme value - e.g. **GaAS** - to the other - e.g. **GaP**.

- **Band gap**: If we have no choice but guessing, your best guess would be exactly as above: The band gap probably changes from one extreme value to the other one - somehow
- **Direct - indirect band gap**: That's where guessing ends - except that for very small or very large ***x***'s we probably get whatever the pure material will have.
- **Index of refraction**: Well - we will have a smooth change, most likely.

OK - we are now ready for a few diagrams



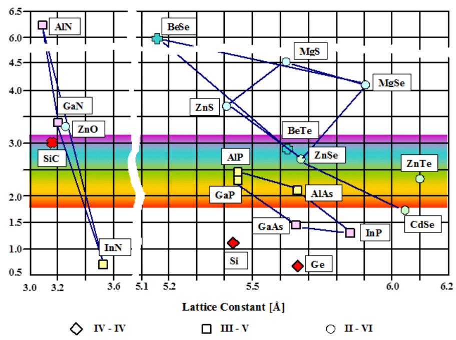
Lattice constant vs. composition for some ternary **III-V's**

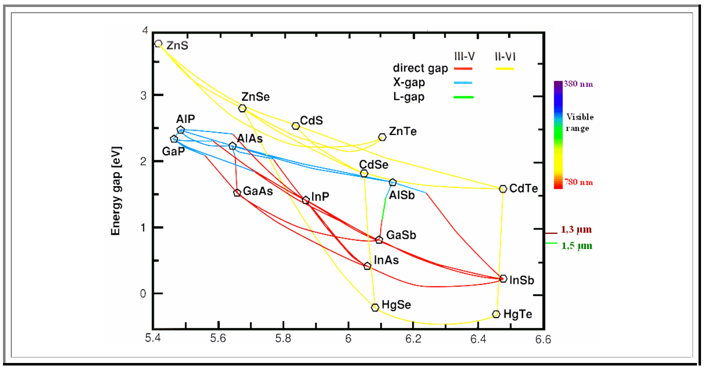


Band gap and refractive index vs. composition for **$Ga_xAl_{1-x}As$**

- So it is pretty much as expected. Pretty smooth changes of lattice constants and index of refraction with composition, but not strictly linear with composition. Notice that the lattice constant hardly changes going from **GaAs** to **AlAs**. This will have tremendous technical consequences.
- The band gap case shows two curves - direct and indirect band gap for all compositions. Remember that in wave vector (=***k***-space you might have all kinds of band gaps and only the smallest one left after "adding up" is what we call "the" band gap. In the picture above, the "direct" band gap "wins" for ***x* <** ≈ **0,5**; if you go more in the **AlAs** direction, it will be indirect.

We are now ready for a first glimpse at the semiconductor "**Master Graph**":





- We see a large number of semiconductors in a band gap - lattice constant plot. We have two plots because either one is a bit restricted. The spectrum of light is schematically superimposed, to give some idea about the relation of the band gap energy to light color.
  We also see a whole range of values for **InN**. The lower one is probably the better one, as it turned out more recently. That tells us that even the most basic property of a semiconductor material is not always ewasy to assess.
- Lines connecting two semiconductors indicate that some mixture of the two is possible, and how the lattice constant and the band gap will behave. For a **HgTe - HgSe** mixture, for example, the band gap would decrease coming from both ends at first. However, the upper diagram does not have all possible lines drawn in.
- Look at the **GaAs - AsAl** case in the lower diagram. You see that the lattice constant does not change very much and that the band gap changes from direct (=red line) to indirect (=blue line) as soon as you get **AsAl** "heavy". What we also see it that the common red **LED** is *not* made from **GaAs** but from e.g. **$Ga_{0.7}Al_{0.3}As$**.

It looks like we have a great selection of semiconductors and their mixtures to chose from.

- ***Alas***! Choosing is one thing, *making* the semiconductor of your choice is something else. That's were *semiconductor technology* comes in.
- In reality, only a few of the many semiconductors shown in the Master Graph could be tamed to perform by now. That's good news because it leaves something to do for *you*.

Optoelectronics - A Few Products

Optoelectronics is a formidable and strongly growing field with many facets. Here we can only look at a few products in some arbitrary selection

Light emitting diodes
Where do we find **LED**'s now, and what is going to happen to the field? There is a long story to this question, we can only look at some major points here.

- We have **LED**'s for all the little lights dotting every product that needs electricity - ***TV'***s, dashboards in cars, coffee makers, ... the list is rather long. There are two major and some minor technical requirement:

  1. Must be extremely cheap (**< 1 €** per **LED**); otherwise no mass market.
  2. Must last for many years because you cannot change or replace it.
  3. Should come in all colors (including infrared (***IR***) for remote controls)
  4. Should have low power consumption.
  5. Should have defined angular dependence of emittance.

- The first two points are *musts*; the next three may be ***negotiable***. For informations about the state of our coffee machine or **TV** we don't really need all colors. In fact, blue **LED**'s are a rather young achievement; they necessitate the mastering of **GaN**, which happens long after red **LED**'s were already ***ubiquitous***. Low power consumption is nice, but for the low intensity **LED**'s it doesn't matter all that much. For some applications you want to see that your machine is on from all angles - your **LED** thus should emit in all space angles; for some other uses you want it more directed.
- Then we have **LED**'s replacing regular light bulbs, or at least the light bulb in your flash light. In other words, they are competing against long established technology and must be cheaper or better. What are the requirements?
  Class Exercise: *Answer the question and compare your answer to the list above.*
  Class Exercise: *What is the state of the art?*
- Next we have special **LED**'s, e.g. for *infrared* light. Here is a link illustrating unexpected uses of **IR LED**'s right at the Institute of Materials Science in Kiel

So what do we need in terms of semiconductors and *optoelectronics* technology? Let's start a list.

- Band gaps in direct semiconductors with energies fitting all the photons or **h·ν** wanted - **0.5 eV - 4 eV** would be fine, for example
- High efficiencies of operation, i.e. Power in (=***U·I***) / light power out should be close to **1** meaning **100 %** efficiency.
- Absolute light power should be large ("**100** Watt light bulb")
- White light should be possible.
- (Product) Lifetime is a concern.

BNow let's look at more optoelectronic products. You do that:

Class Exercise: ***Amend*** *and discuss the list given so far.*