9.1.2 Optoelectronic Devices

Remarks

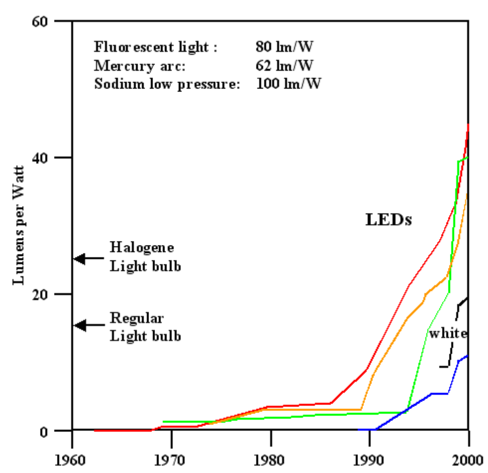
- This module will start in a very superficial way. It will be neither complete in the sense that all important devices are mentioned, nor exhaustive in the sense that the most important specifics of the devices will be included
  - In time, it is hoped, this module will become more volume and depth from the work of the students in the accompanying seminar.

Light Emitting Diodes

- Light Emitting Diodes or **LED's** are the cornerstone of optoelectronic products. Very roughly they are used for two main product lines and for one speciality:
- **1. Signal lights** All those little red, yellow, green or blue lights (sometimes *blinking* annoyingly), mostly used for indicating that something has been turned on, is in a certain mode, or simply is just there (e.g. blinking red bicycle lights).
  - The main requirement for signal light **LED's** is that they come in many *colors* (so **designers** of dashboards etc. are not limited in their creativity; an important condition considering that designers appear to be limited in many other respects) and that they are *cheap*.
  - Nowadays (**2008**) we do have all colors - including "white" - but that was not always so. For generating a specific "color" including white you can go three routes:

    1. Take a semiconductor with the appropriate bandgap. This generates a "true" color, i.e. light around one wavelength as given by our "master diagram" from before.
    2. Take semiconductors that generates **UV** or at least high-energy light and use it to excite some fluorescent material - exactly like in fluorescent light tubes. That can produce white light or any color you find a fluorescent material for.
    3. Take three semiconductors that produce "**RBG**", i.e. red - green - blue, in such an intensity mixture as to produce the color wanted - exactly at it is done by any screen or display.

  - Obviously the first way is potentially the cheapest as long as you don't require white light. That's why you mostly find **LED's** belonging to the **GaAlAs** family (red), **GaP** family (green) or the nitride family **GaAlN** (blue to **UV**). Going from red to blue / **UV** also mirrors the history of **LED** development.



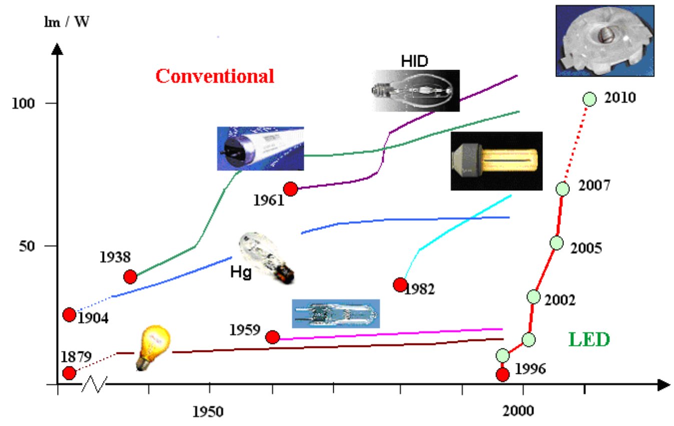
Source: M.R. Krames et. al., Applied Physics Letters, 75[16], pp. 2365, (1999) and Scientific American, Feb. 2001

  - The orange **LED** dscribed in the article mentioned above already had an efficiency of **> 100 lm/W**, and today (Feb. 2008) **150 lm/w** white **LED's** can be purchased, for example from **Nichia** (the company that pioneered the blue / white **LED**). But now we moved already into the second topic:
- **2. Light** With the advent of the blue / **UV GaN**-based **LED** in **1993** (that comes with a quite interesting story around its inventor, Shuji **Nakamura** and the company he was then working for (Nichia)), making white light with **LED's** was possible for the first time.
  - For general lighting purposes - your room, the street, a congress hall, the street in front of you bicycle or car, - you name it - you need first of all *white light*. After you can do that with **LED's**, you need:

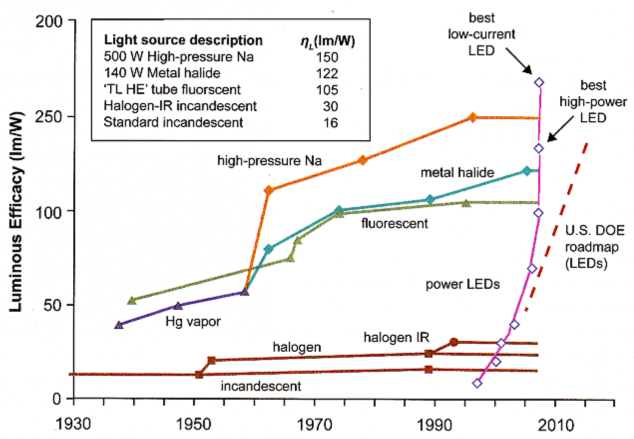
    - High **efficiency** as measured by lumen / Watt (**lm/W**) or by total "plug efficiency" in **%**, meaning the ratio of light energy out to electrical energy ***UIt*** in.

- High *intensity*. It is not good enough to have a high-efficiency light source if the best you can offer produces the same intensity as, let's say, a **20 W** conventional light bulb.
- Large **life time**. You do not want to change your light fixtures too often. For something in the better quality region, you want several years of operation time at the least.
- Low *price*. The price you can get for your white light **LED** depends on what you offer. If it is much better than a regular light bulb, it does not have to be "cheap" - but it still must be worth its price.

The picture below shows the efficiency of white **LED's** vs. existing light sources:



Based on information provided by **Osram**



Light-emitting diodes versus conventional light sources. © 2007, IEEE

The insets symbolize the type of "light bulb" sufficiently; the one belonging to the purple line (the top performer of the "classical" light sources) is the metal halide "bulb", belonging the the "high intensity discharge" (***HID***) type of light source. If you compare the development of the white **LED** to all the other light sources, you get a first impression why everybody in the lighting business is so excited about **LED's** as the light source of the future. Potential energy savings are enormous!

A quick word to the unit "**lumen**" and to absolute efficiencies:

The "*lumen*" (***lm***) is the **SI** unit of the *perceived* power of light; it measures the luminous *flux*. Now the natural way to measure the flux of light would be to measure the *energy flux* of the light. Since the eye, however, is not equally sensitive to the various wave-lengths it can see, the lumen corrects for this.

As far as converting **lm/W** into absolute efficiency goes, we have the following approximate relations

- **(10 - 15) lm/ W ⇔ (5 - 9) %**
- **(70 - 100) lm/ W ⇔ (25 - 35) %**

With respect to efficiencies, **LED's** do have a bright future, indeed. What about the other criteria?

Product life time is not a problem but an asset. Well-made **LED's** will last for **>10** years, outperforming more or less all other light sources.

The problem is: *intensity*. The light is typically produced in a small volume (great for focussing etc.), and if you put a power of let's say **100 W** into a volume of <**1 mm^3**, you better have some concept of keeping the temperature down.

Closely related is the problem of plug compatibility, meaning that you want to use **230 V 50 Hz AC**, **110 V 60 Hz AC**, or whatever your country has as its consumer electrical energy standard. A **LED**, however, is a forwardly biased **pn**-junction, running at something like **3 V DC** (and then **33 A** if you want **100 W**). While this is an electrical engineering problem, it is still a big problem.

The (inorganic) materials used for both applications (always as thin layers) are once again:

- Aluminium gallium arsenide (**AlGaAs**) — red and infrared
- Aluminium gallium indium phosphide (**AlGaInP**) — high-brightness orange-red, orange, yellow, and green
- Gallium phosphide (**GaP**) and Aluminium gallium phosphide (**AlGaP**) — green
- Gallium arsenide phosphide (**GaAsP**) — red, orange-red, orange, and yellow
- Gallium nitride (**GaN**) and Indium gallium nitride (**InGaN**) — near ultraviolet, bluish-green and blue

Laser Diodes

Semiconductor Lasers will be treated in some more detail in module 9.2.2. Here we simply note that the theory of (semiconductor) Lasers is rather complex, but the technology is not.

- In principle, many **LED's** "automatically" become a Laser if you run a very high current through them (producing a lot of light) without destroying them first. It is therefore not too difficult to produce a Laser diode in the Lab - all you need (haha) is very efficient cooling of your experimental **LED** device.
- You may know already that Lasers always need some kind of optical feed back, usually provided for by mirrors, and ask yourself where the mirrors are if we use a simple **LED** as Laser. The answer is that plan-parallel surfaces of the semiconductor might be already sufficient for that because the interface semiconductor - air does act as a "semi"-transparent mirror and that might be good enough.

Laser and optics of CD player.

The truth, however, is that it often takes many years after a certain new **LED** has been marketed, before the long-lived, reliable and cheap Laser diode follows.

- The first **GaN**-based blue **LED's** were on the market around **1993**, whereas the blue **GaN** based Laser had to await **2005** or so (in **2006** SONY, for example, still had major production problems).

Using semiconductors for making a Laser is just one way for making Lasers - you can use other solids, liquids and gases for that. This brings up the question of pro and cons - what are the advantages and disadvantages of semiconductor Lasers?

- Look at **CD** and **DVD** or now **blue ray** disc drives - the are the major market for semiconductor Lasers besides the very pedestrian "Laser pointer". The advantages are obvious:
  - Very cheap.
  - Very small.
  - Electric energy supply at low voltage.
- The major disadvantages are
  - Low power at decent quality (around **1 W** maximum).
  - Limitations as to color (= frequency).

The cheap and reliable semiconductor Lasers are actually the **enabling** devices for all this memories! No suitable Laser - no discs.

Sorry - your Laser *pointer* just can't be turned into the Laser *gun* you might fancy for fighting those aliens if you are a male (or, in your adult life, for cutting metal or other materials). For this you need other Laser types which can deliver real *power* - far heavier, bulkier and far more expensive than your semiconductor Laser.

- Of course there are constant optimizations and new developments - newer and better semiconductor Lasers are frequently announced. We haven't seen the last of this yet.

Displays and *OLED's*

Take a million or so **LED's**, arrange them in a matrix, and make sure they can be individually addressed - you now have a **display**.

- If you make your display with individual **LED's**, soldered together somehow, you will get an expensive big display with lousy resolution - the kind of boards you see on Times Square or other places that have been taken over by the evil advertising people.
- If you *could* make your **LED's** tiny in the lateral direction *and* all of them close together, i.e. on *one* substrate, *and* for all three **RGB** colors *and* individually addressable, you would have a **flat panel display** that would be great for **TV**, computers, cell phones and laptops because it could have a high energy efficiency.

OLED based **TV**
Courtesy of **Samsung**

- Unfortunately, the possible substrates for inorganic semiconductor **LED's** are far too small (we have only the **III-V** single crystals, essentially **GaAs**, **SiC** and perhaps Al_2O_3 (= Sapphire)) and those potentiial substrates do not come even close to what would be required.
- Fortunately, an unexpected discovery made accidentially in the **70ties** by **Shirakawa** in Japan (and to some extent by others before him) has helped:
  - There is such a thing as an **organic conductor**, and an **organic semiconductor** leading to an **organic light emitting diode** - an **OLED**.
  - **OLED's** have only be around for less then **5** years, but we already have flat panel displays based on **OLED's** in cell phones and the first ones for **TV** are announced right now.
- Let's be clear about one thing: *Organic semiconductors* right now are still lousy semiconductors (and extremely sensitive to oxygen).
  - They have a tremendous advantage over inorganic semiconductors, however: they can be very cheap and, far more important, they can be deposited at low temperatures by rather simple techniques on cheap and very large substrates and they are easy to pattern.
  - In other words: **OLED** displays are easy to make, the light emission is **OK**, and the product life time is **OK** at present for consumer items where demands are a bit more relaxed.
- What we are witnessing right now is the beginning of a completely new field of *semiconductor materials science and technology*. Who knows where it will end!