University of Nottingham

Photon sources and photodetectors

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Overview

- Edge emitting lasers
    - Fundamentals physics behind lasers
    - Electrical characteristics
    - Lasers used in telecoms systems
- VCSELs
- Photodetectors

Aims of lecture

- What this lecture is:
    - This lecture aims to give you enough information to understand the operation of laser diodes, light emitting diodes and detectors.
    - It is aimed at helping you understand the devices enough to make component choices when designing telecoms systems.
- What this lecture is not:
    - A solid state physics lecture – I try to avoid derivations where possible.

Further reading

- The book I recommend:
  - **Solid State Electronic Devices 5th Edition by Streetman, Ben; Banerjee, Sanjay published by Prentice Hall (£40/$64)**
  - There are lots of other books on the subject available I suggest you go and browse the semiconductor physics section at your library

Notes

- Very soon after this lecture you will be able to download the notes from the web:

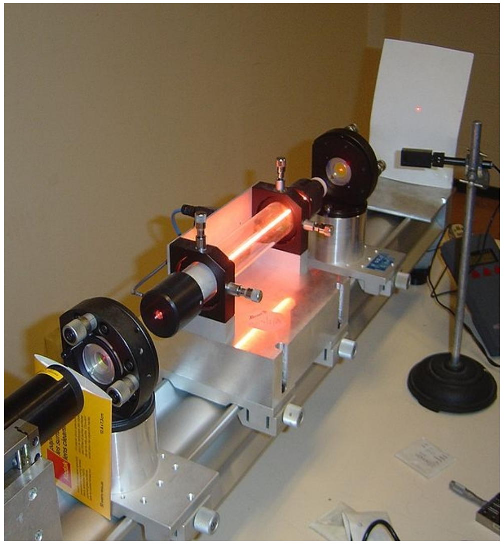
http://www.roderickmackenzie.eu/lecturenotes.html

Lasers

- Lasers are a source of photons first developed in the 1960s used to:
    - Transmit information thousands of km.
    - Cut metal
    - Perform surgery
    - Read and store information
- In fact there is no part of modern life which does not rely to some extent on a laser.
- Before we look at telecoms lasers lets look more broadly at lasers in use today.

Types of lasers in use today:
Gas lasers

- Work by electrically exciting a gas in a tube.
- Typically found in labs and industry – i.e. CO_2 lasers are used for cutting steel
- Power output **~100 W**.



David Monniaux

Types of lasers in use today:
Chemical lasers

- Powered by a chemical reaction.
- They are very powerful
- Power output ~**Megawatts**

Airplane equipped with missile defense laser

- Operate by mixing oxygen-iodine
- Very high power.
- Used to shoot down rockets.

Types of lasers in use today:
Solid state lasers

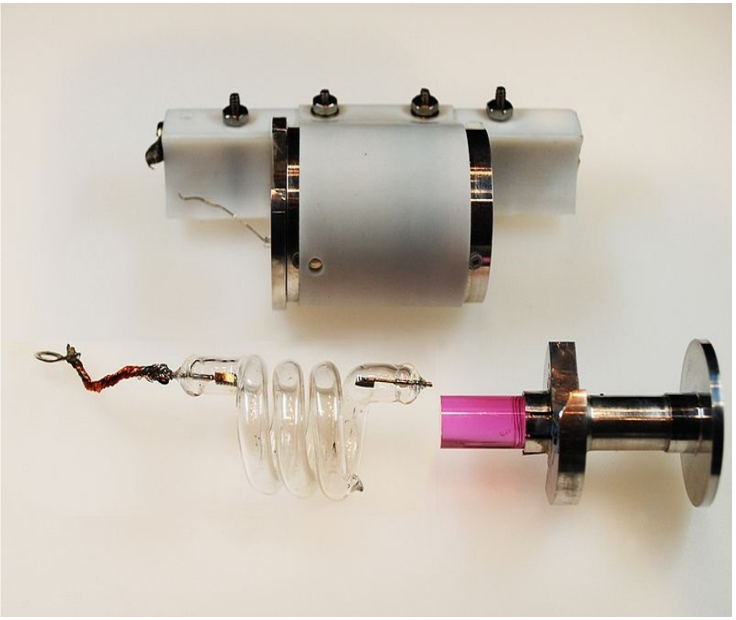
•This was the first type of laser developed.

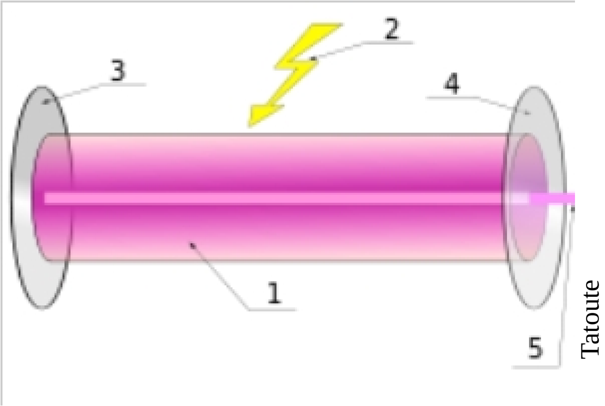
•An external optical source pumps a ruby crystal.

•A modern equivalent would be **Ytterbium-Doped** fiber amplifier used it telecommunication systems

•Can produce up to 100kW of optical energy

•1. Gain medium, 2. Laser pumping energy, 3. High reflector, 4. Output coupler, 5. Laser beam

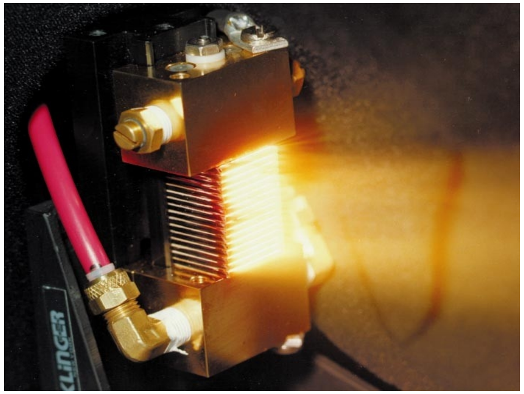




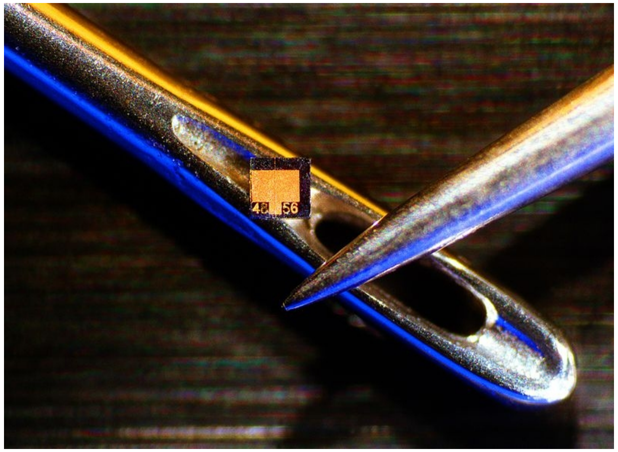
Types of lasers in use today: **Semiconductor lasers**

Semiconductor lasers:

- First demonstrated in 1962
- They are widely used in, photoactive cancer therapy, industrial cutting, intersaterlite comunication, CD, DVD laser pointers....
- They are used also very extensively in our telecommunications infrastructure as photon sources.



High power laser diodes used for cutting steel.



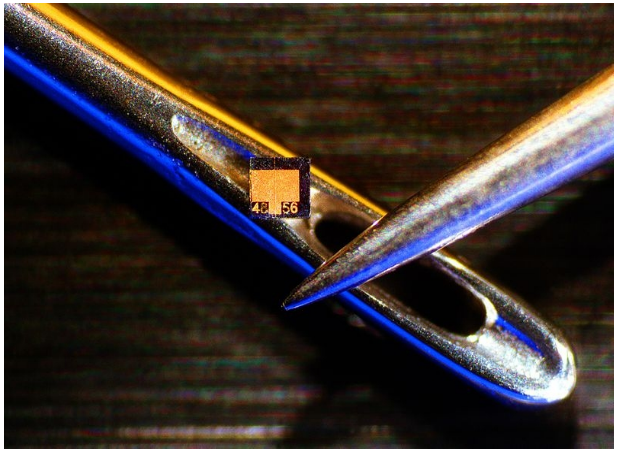
Telecomunications laser

- Power output **10mW** and **~4 W**

Types of lasers in use today: Semiconductor lasers

Advantages:

- Very small
- Efficient
- High beam quality
- Low cost
- Can be directly modulated
  - electrically



Telecomunications laser

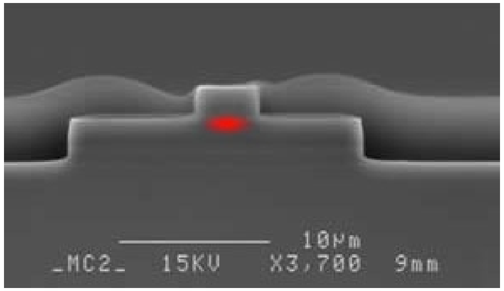
- In this lecture we will cover the fundamental operating principles.
- First let's start by looking at the materials from which they are made……

The material from which semiconductor lasers are made

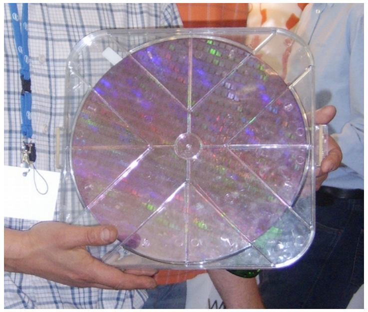
Semiconductor lasers are made of highly ordered, highly pure crystals such as

- Gallium Arsenide (GaAs)
- Indium Phosphide (InP)

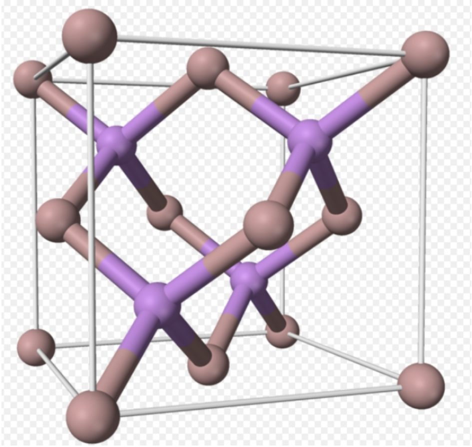
- They are grown atomic layer by atomic layer on a substrate.



A SEM image of a laser diode (fast access project)

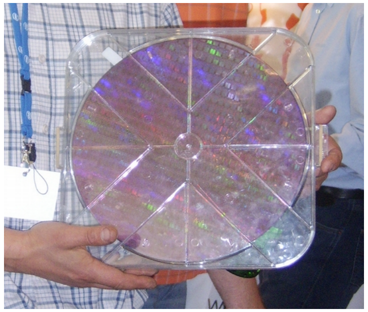


Wafer

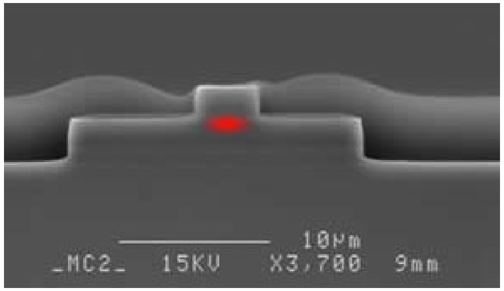


The crystalline structure of GaAs

Molecular beam epitaxy



Wafer



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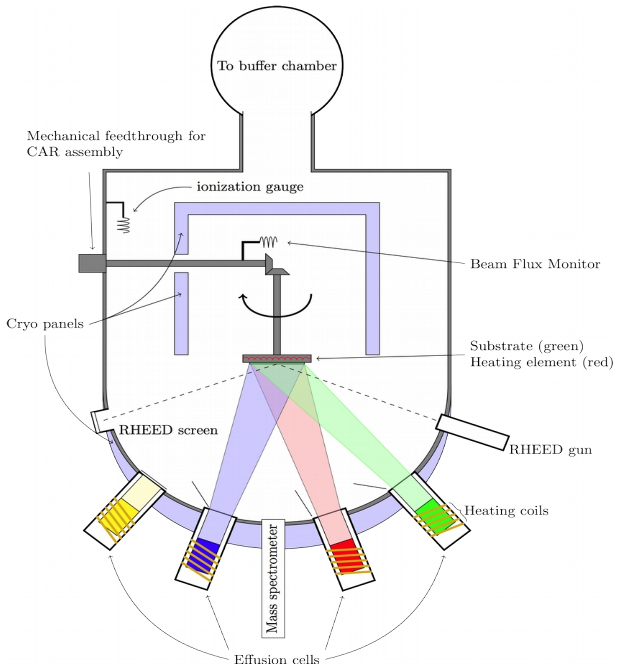
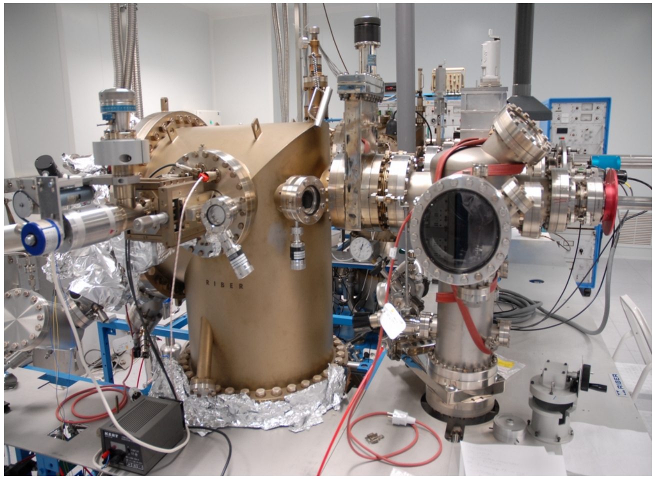
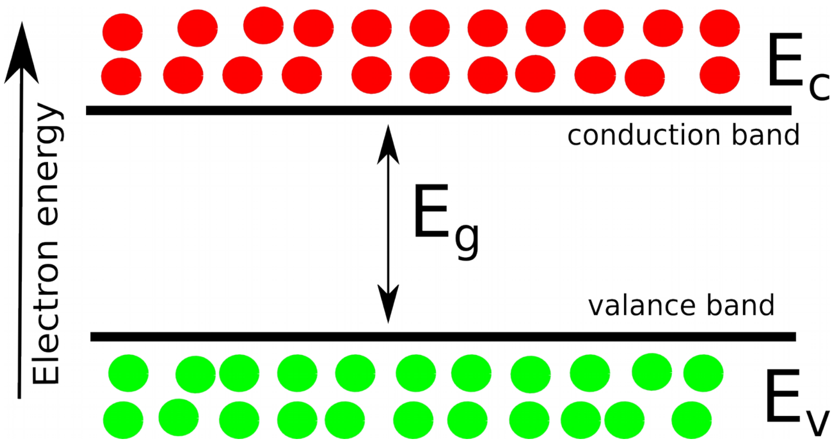


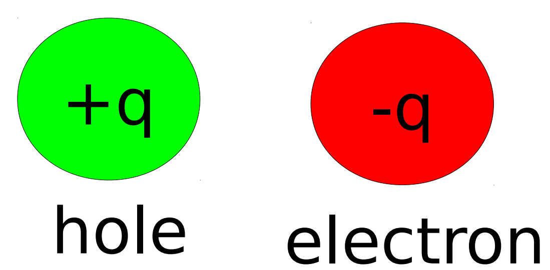
Wikipedia en Vegar Ottesen



Fundamental principle of semiconductors

- A semiconductor is a special type of conductor where positive charges and negative charges can be in the same type of material.
- Electrons are transported in the conduction band (Ec)
- Holes are transported in the valance band (Ev)





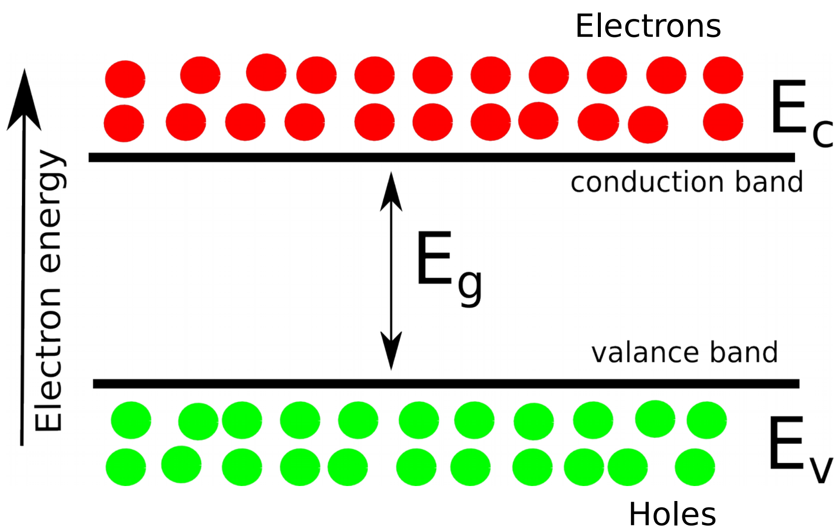
$q = 1.60217657 \times 10^{-19}$ coulombs

Fundamental principle of semiconductors: **The band gap**

•The energetic gap separating the electrons and holes is called the band gap (Eg).

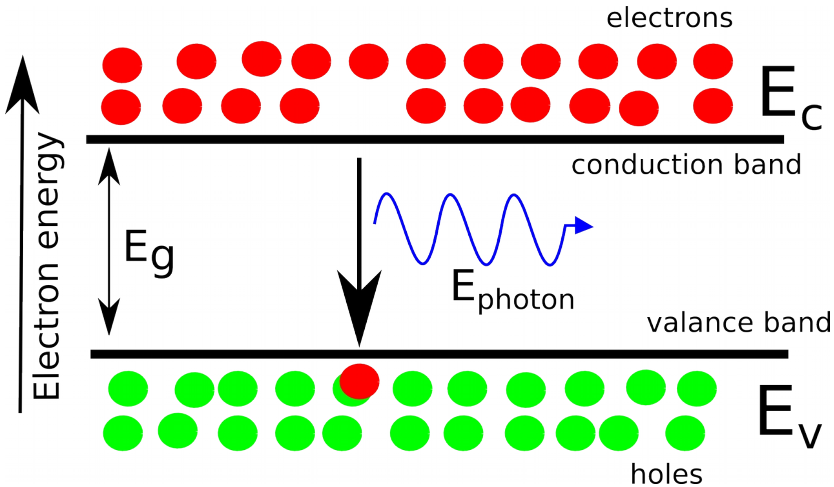
•For semiconductors this is typically between 1 and 3 volts.

•For insulators such as SiO_2 is can be as high as 8V.



Fundamental principle of semiconductors: **Spontaneous emission**

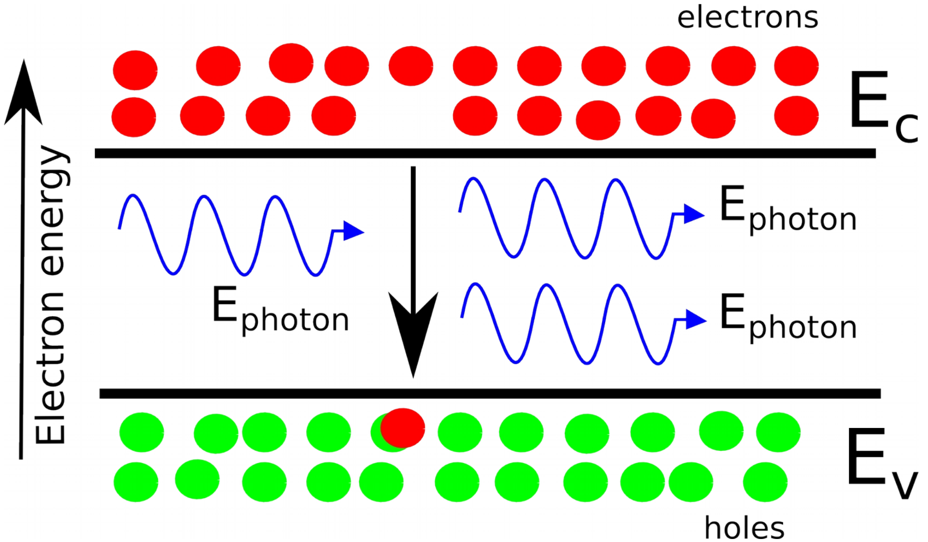
- An electron can drop out of the conduction band and recombine with a hole in valance band.
- In doing so the electron looses energy Eg.
- Energy can not be destroyed so this energy is emitted as a photon of energy E_{photon}.



$$E_{photon}=E_g$$

Fundamental principle of semiconductors: **Stimulated emission**

- Another way electrons and holes can recombine is for a photon of energy E_{photon} to stimulate the emission of another photon of energy E_{photon}.
- This is called stimulated emission.

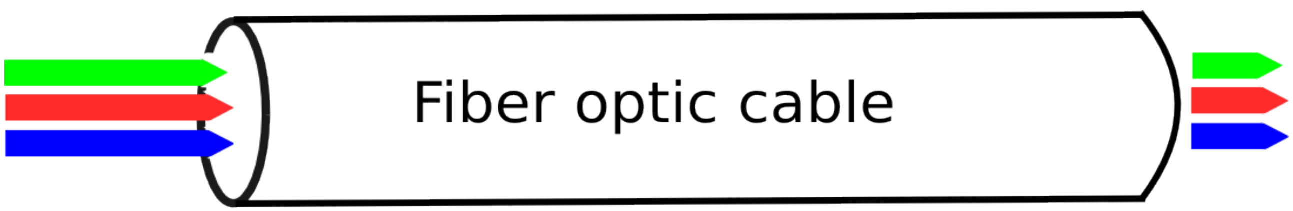


The photons emitted will have the same energy, direction and phase as the incoming photon.

Fundamental principle of semiconductors: **Stimulated emission**

The photons emitted will have the same energy, direction and phase as the incoming photon.

- This is very important for telecommunications
- Because if all your photons have the same energy, it means all your light will be at the same wavelength.
- So you can put multiple wavelengths of light down one fiber without them interfering with each other.



Relationship between energy and wavelength (Review)

$$Energy = hf$$

h = planks constant
(6.62606957×10^{-34} m^2 kg/s)

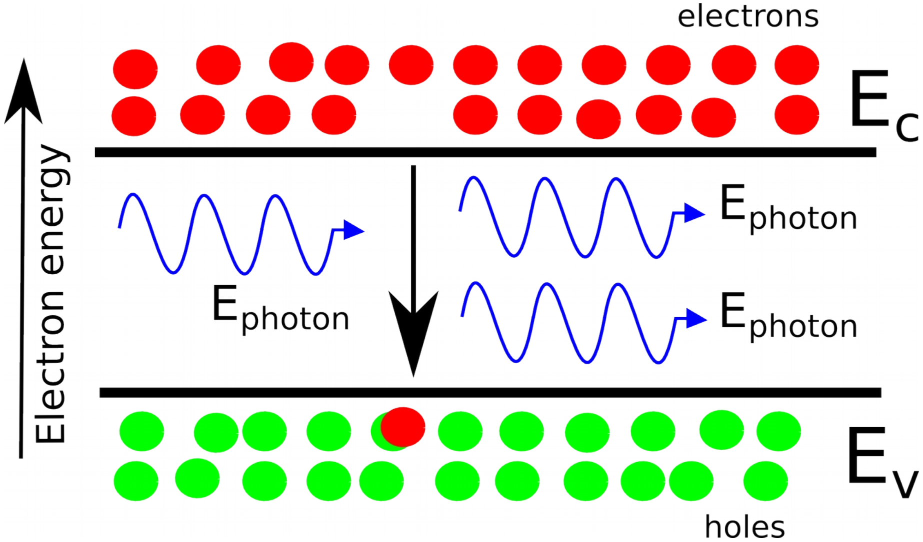
f = frequency of light

$$c = f\lambda$$

λ = wavelength of light

$$\lambda = \frac{hc}{Energy}$$

$$\lambda = \frac{hc}{Eg}$$

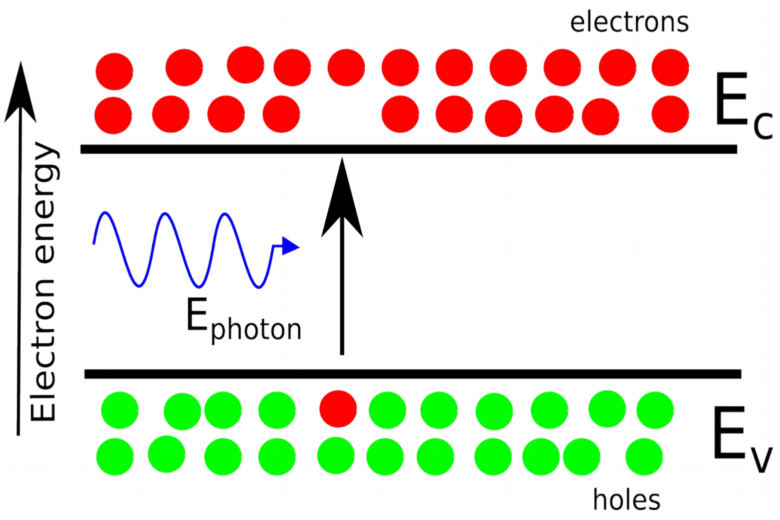


- Therefore the band gap of your material will dictate the wavelength (color) of light emitted by your laser.

Fundamental principle of semiconductors: **Absorption**

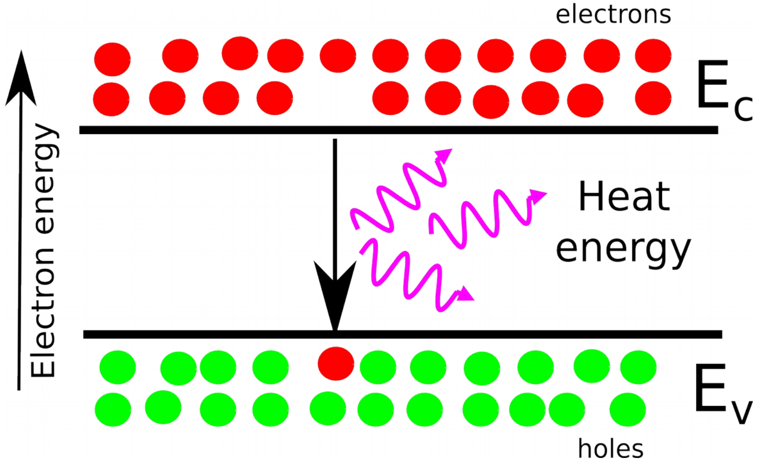
- Light can also be absorbed by semiconductors.
- In this process an electron from the valance band is excited to the conduction band.

- This process is used in photodetectors to detect light.
- However in lasers this process is not desirable.



Fundamental principle of semiconductors:
Dark recombination (undesirable)

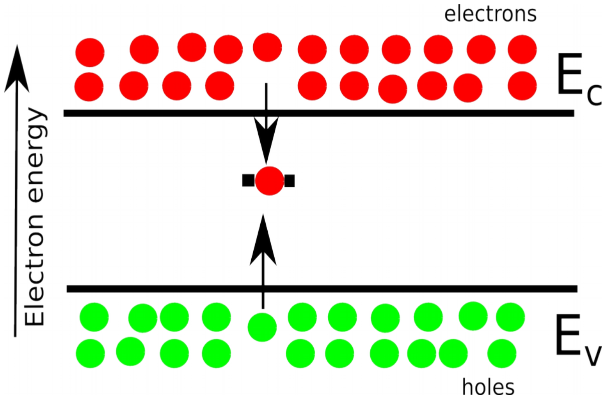
- Spontaneous and stimulated emission are not the only types of recombination mechanism in semiconductors.
- There is also dark recombination where an electron relaxes from the conduction band to the valance band emitting heat (phonon) instead of light (photon).



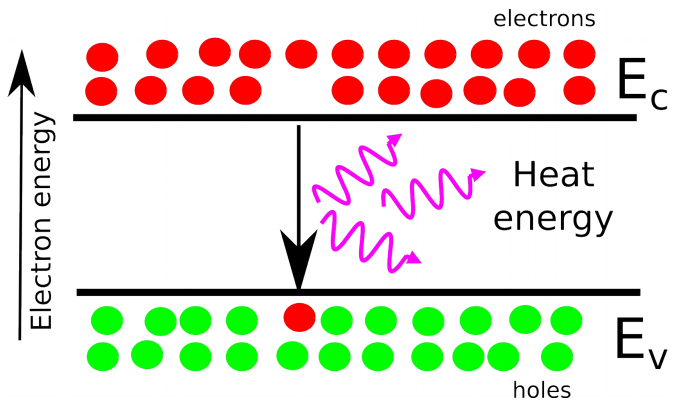
Dark recombination is unwanted in photonic devices as it produces no light..

Fundamental principle of semiconductors: **Types of dark recombination**

•Schottky-Read-Hall: This happens via trap states:



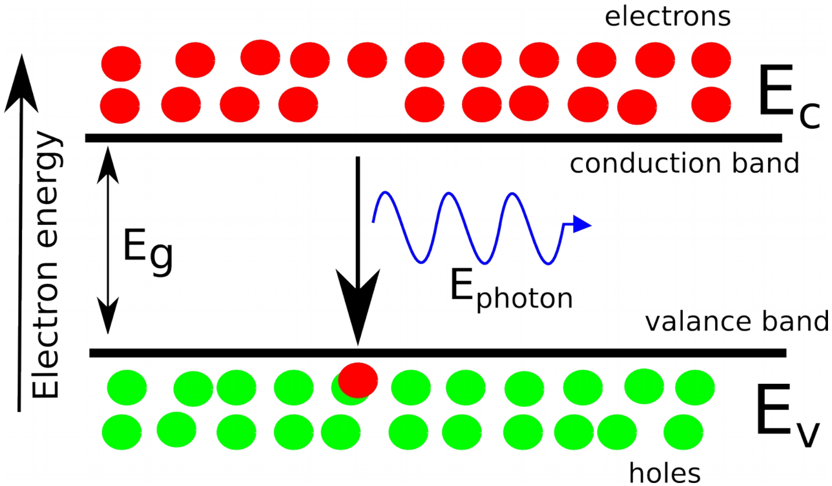
•Band to band recombination: Free electrons recombine with free holes.



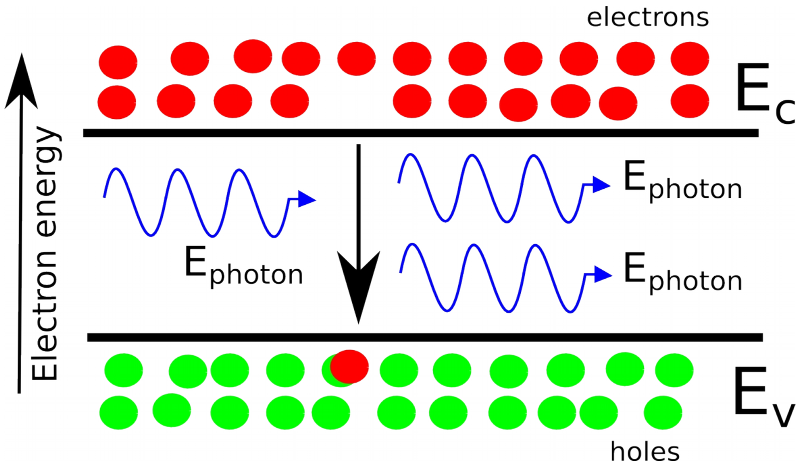
•There is also Auger recombination.

Recap of fundamental processes in semiconductors

•Spontaneous emission where an electron and hole spontaneously recombine to produce a photon.

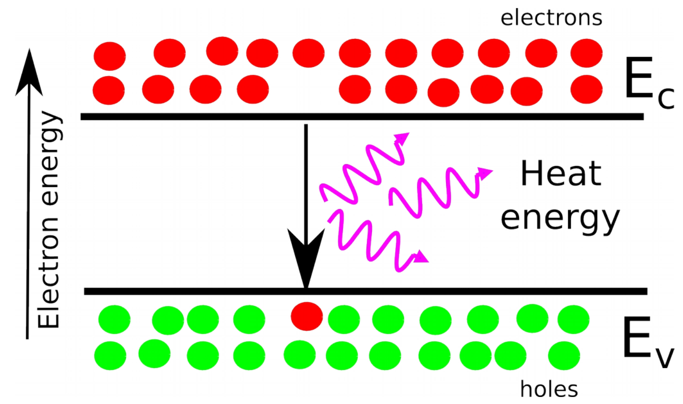


•Stimulated emission where a photon causes the generation of another photon of the same wavelength and direction.

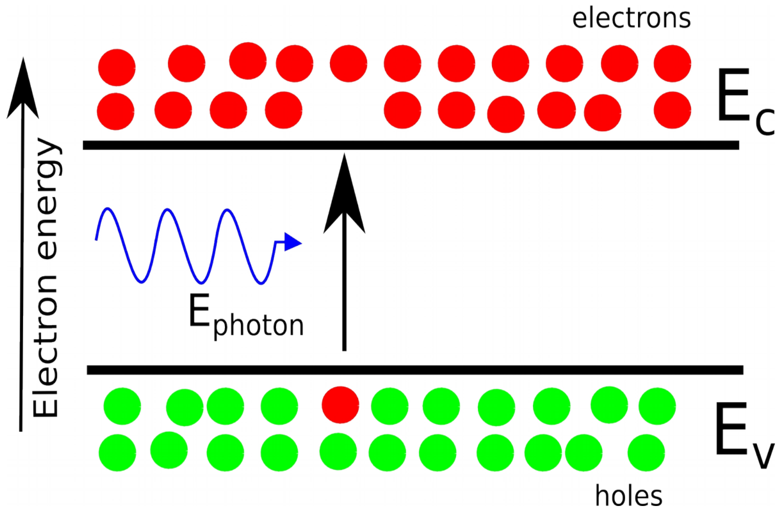


Recap of fundamental processes in semiconductors

•Dark recombination, which is unwanted where an electron and hole recombine to produce heat.



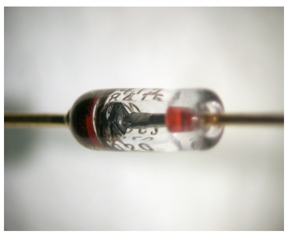
•Absorption where a photon is absorbed. Desirable in photodetectors – undesirable in lasers and LEDs.

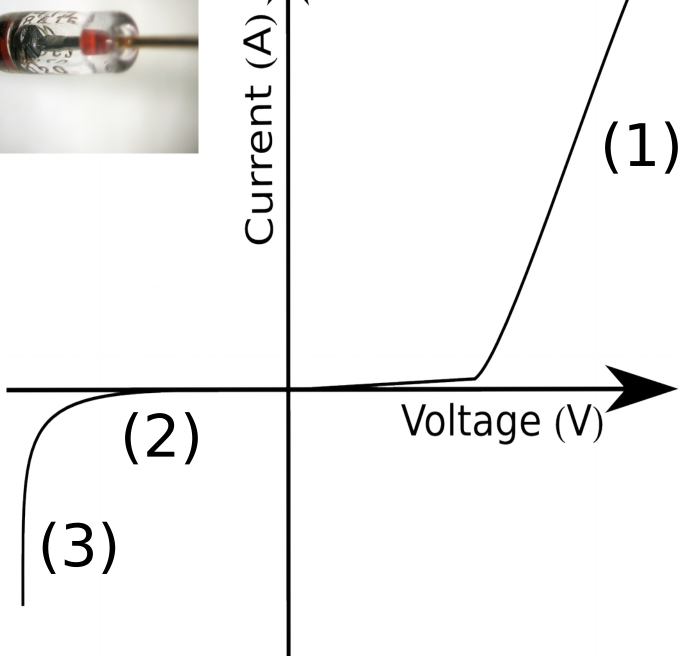


Diodes
Fundamental properties

• Before we look at **laser diodes** (LD) or **light emitting diodes** (LEDs) let's try to understand a standard diode.

Morcheeba at en.wikipedia





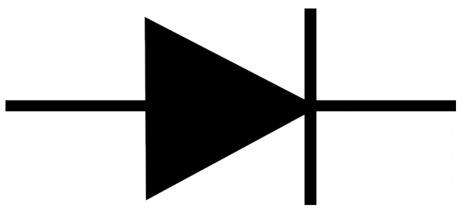
Standard diode IV curve

• A diode is a device made of a semiconductor material which has the following properties:

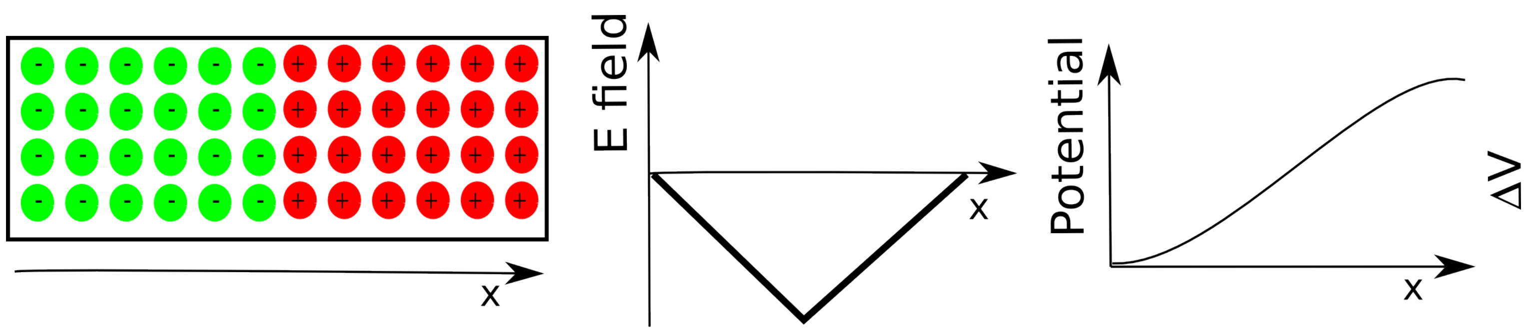
1) Conducting
2) Blocking
3) Breakdown

How do diodes work? (1/4)

- One side is rich in holes and the other is rich in electrons.
- Because of the excess carriers a field builds up.



- A potential is associated with this field (Gauss's law)



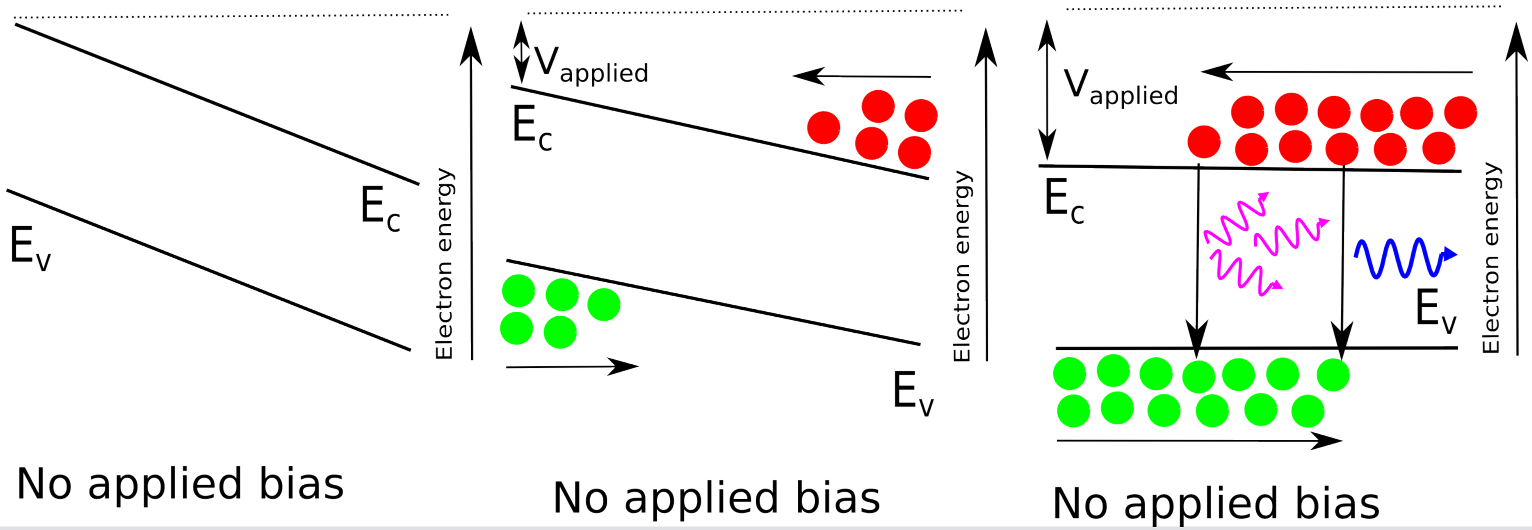
Charge distribution

Electric field

No applied bias

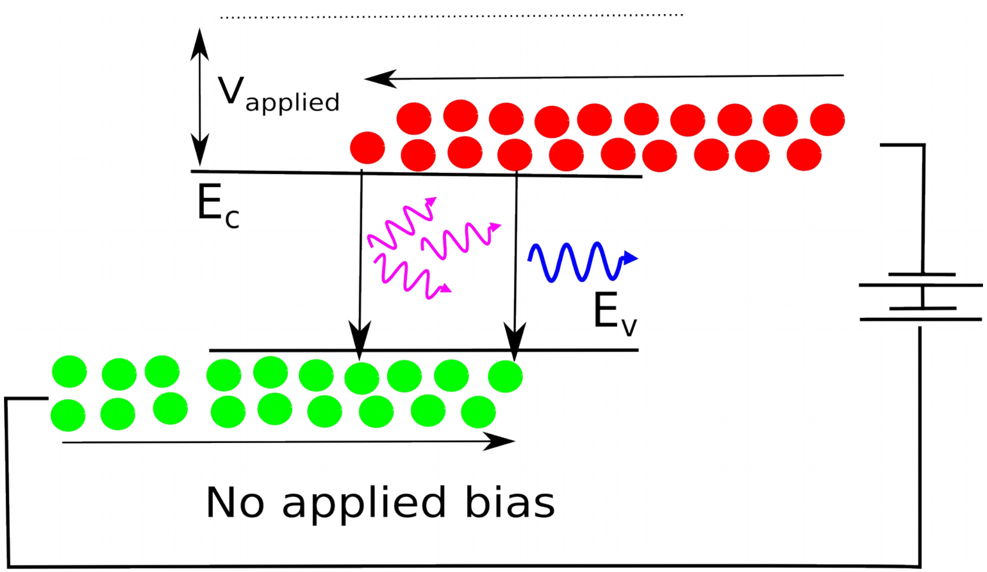
How do diodes work? (2/4)

- As we apply a bias ($V_{applied}$) to our diode the bands bend downward
- The result is that electrons and holes can be injected into our device.
- Where they meet in the middle they recombine.



How do diodes work? (3/4)

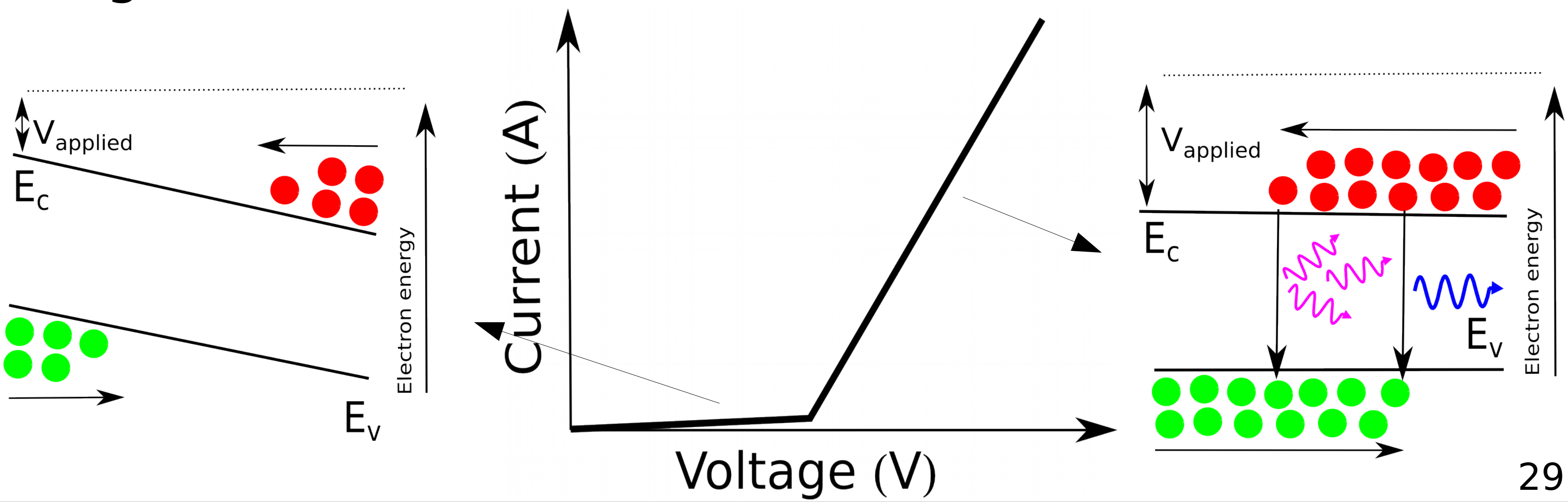
•The electrons and holes that recombine must be replaced so we get current.



How do diodes work? (4/4)

YouTube example

- Below threshold the electron and hole populations are kept apart from one another.
- Above threshold they spatial overlap and recombine.
- This allows more carriers to enter the device and thus we get current



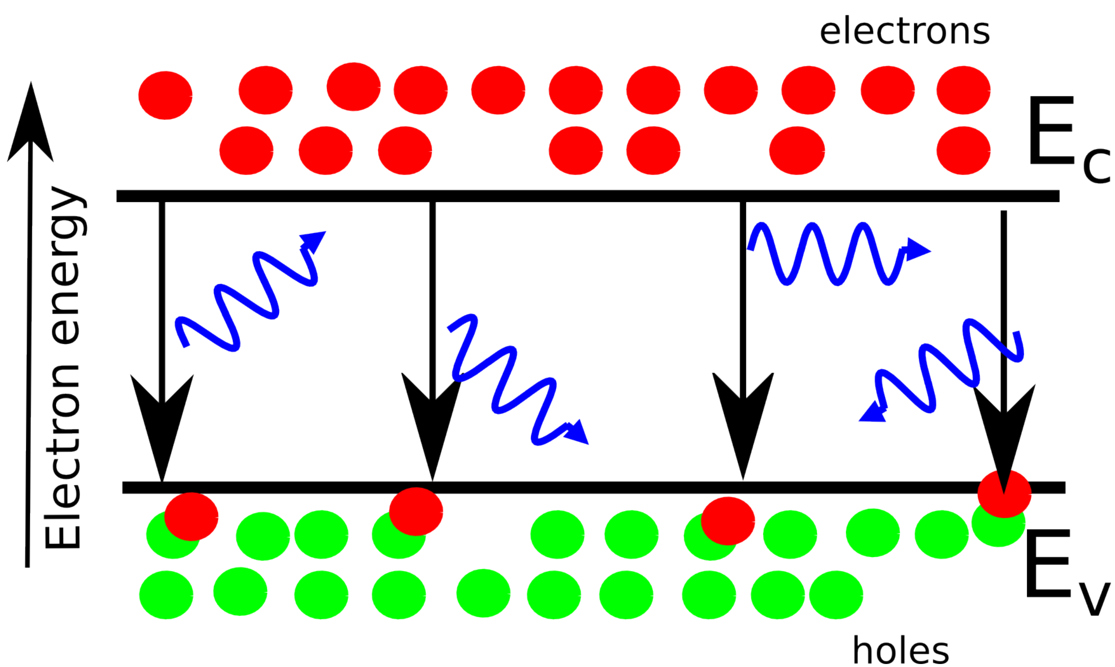
A simulation of a diode

- In a standard diode dark recombination dominates
  - i.e. there is no light; all recombination results in heat being generated.

YouTube example

From standard diodes to Light emitting diodes (**LEDs**)

•In light emitting diodes spontanious emission dominates and light is produced in forward bias.

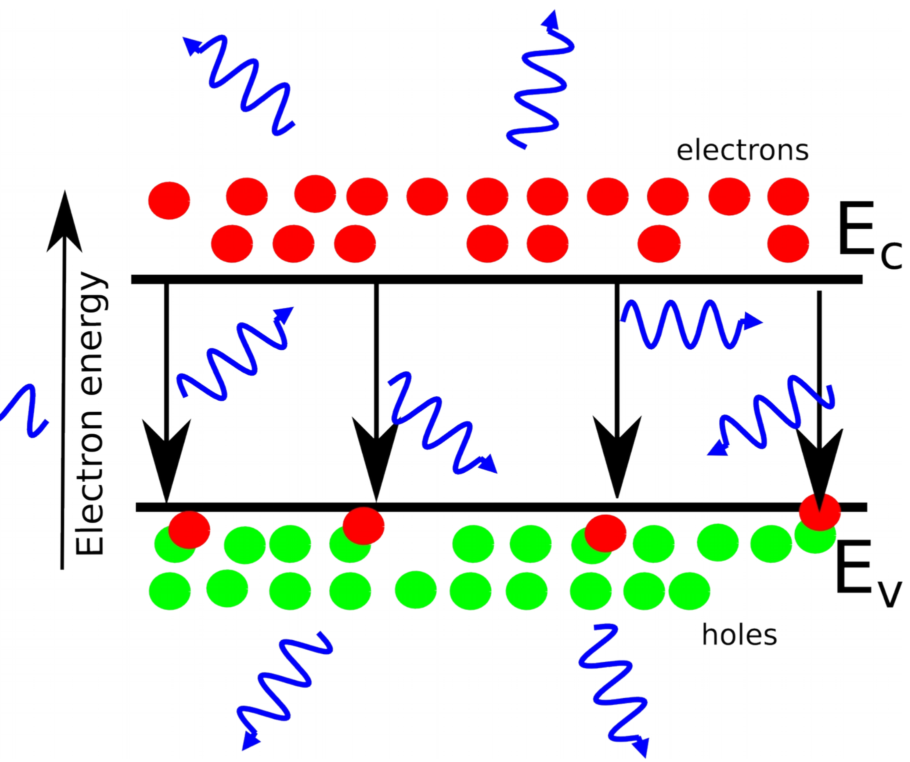


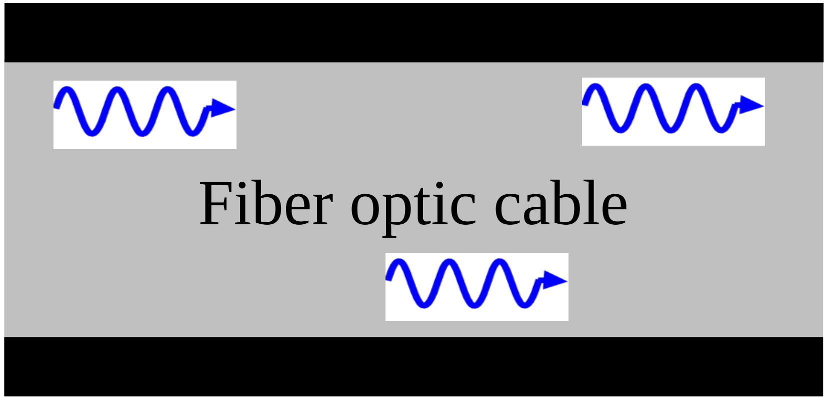
•Each one of these emission events is random.

•The photons go in a random direction.

From LEDs to Laser diodes

Can you imaging trying to couple light from an LED into a fiber:

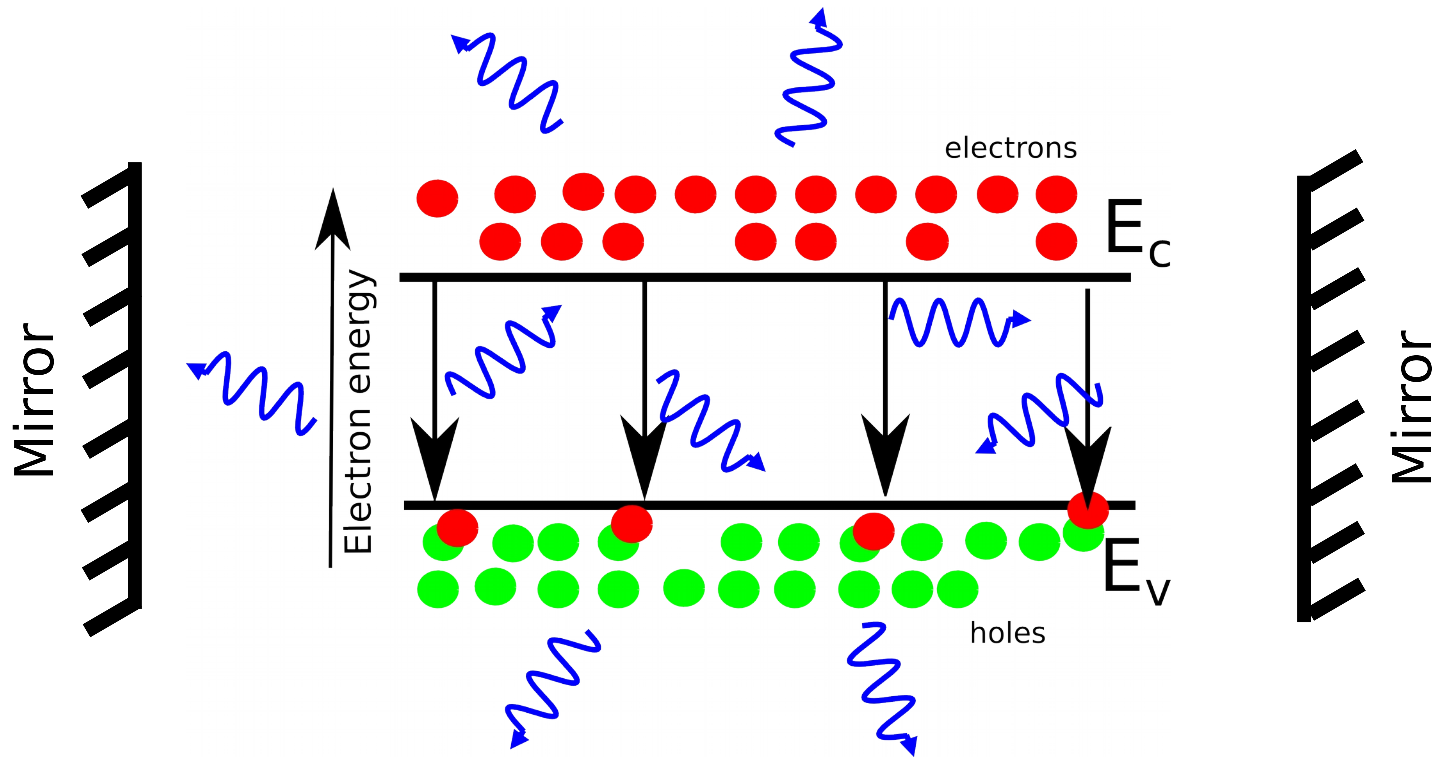




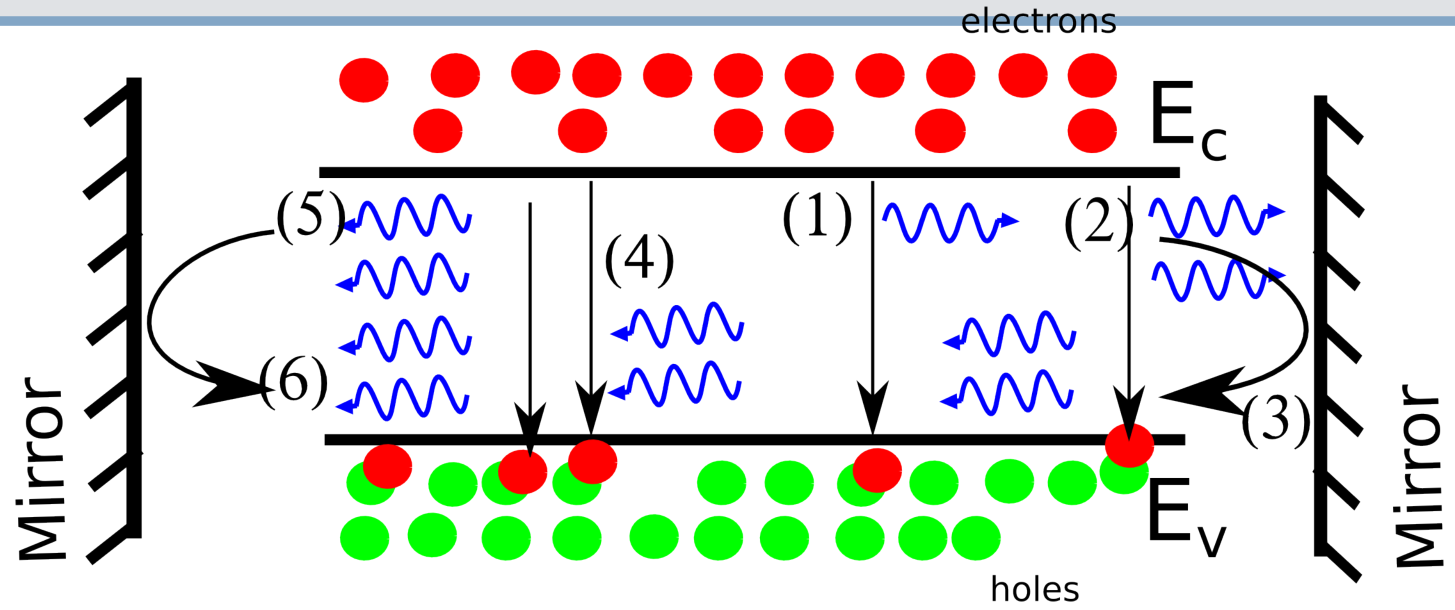
It would not be very efficient

From LEDs to Laser diodes

To try to improve the situation we place two mirrors on either end of our LED diode to form a **resonant cavity**.

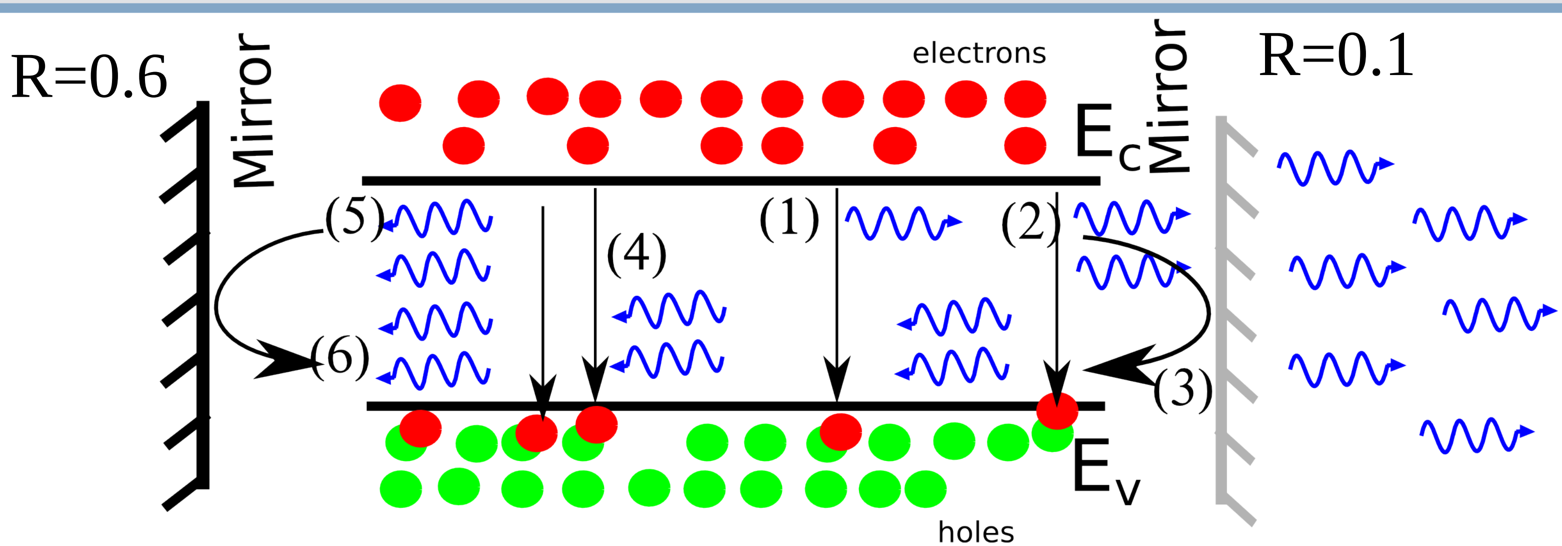


From LEDs to Laser diodes



1) A photon is emitted (stimulated or spontaneous emission), 2) the photon stimulates the emission of another photon, 3) the two photons get reflected off a mirror, 4) the two photons cause more stimulated emission and 5) the photons get reflected off the back contact.

From LEDs to Laser diodes

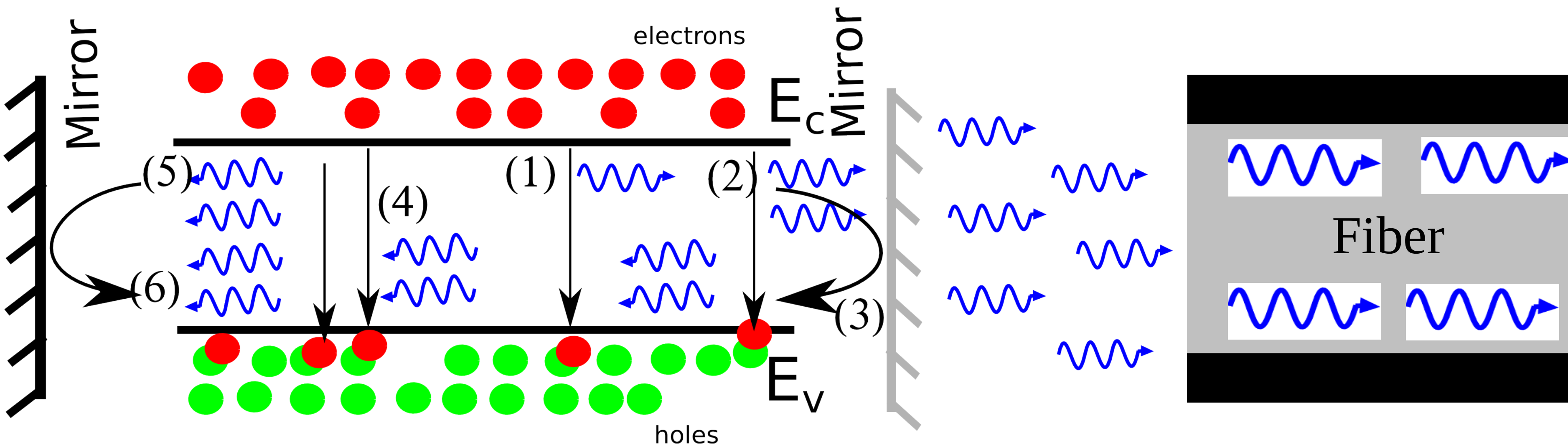


•Key to remember is that each photon causes stimulated emission.

•This means that each photon generated will be in the same direction/phase as the last

•The mirrors allow a photon field to build up. If we make one mirror semi transparent we get coherent light out of our device

From LEDs to Laser diodes

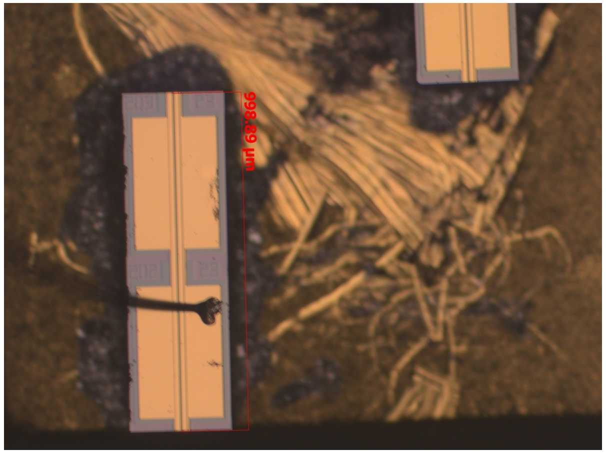


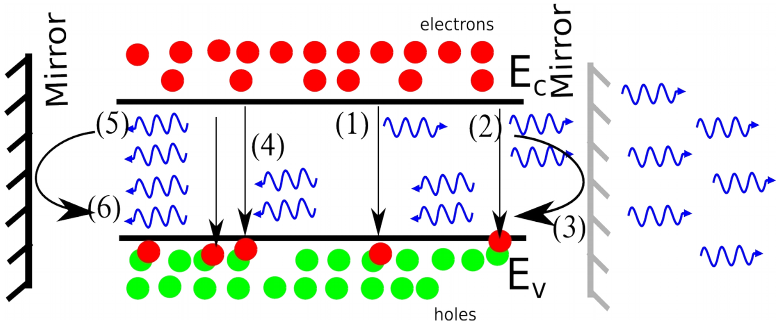
- Much more efficient coupling into a fiber.

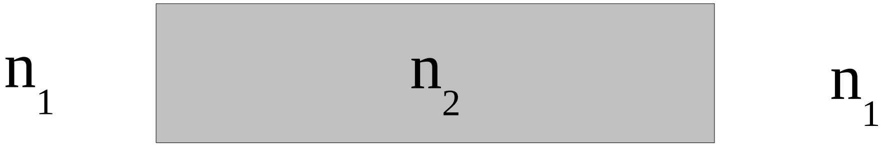
Laser mirrors

- The mirror is formed by simply using the air semiconductor interface.

$$R=\left|\frac{n_2-n_1}{n_2+n_1}\right|$$

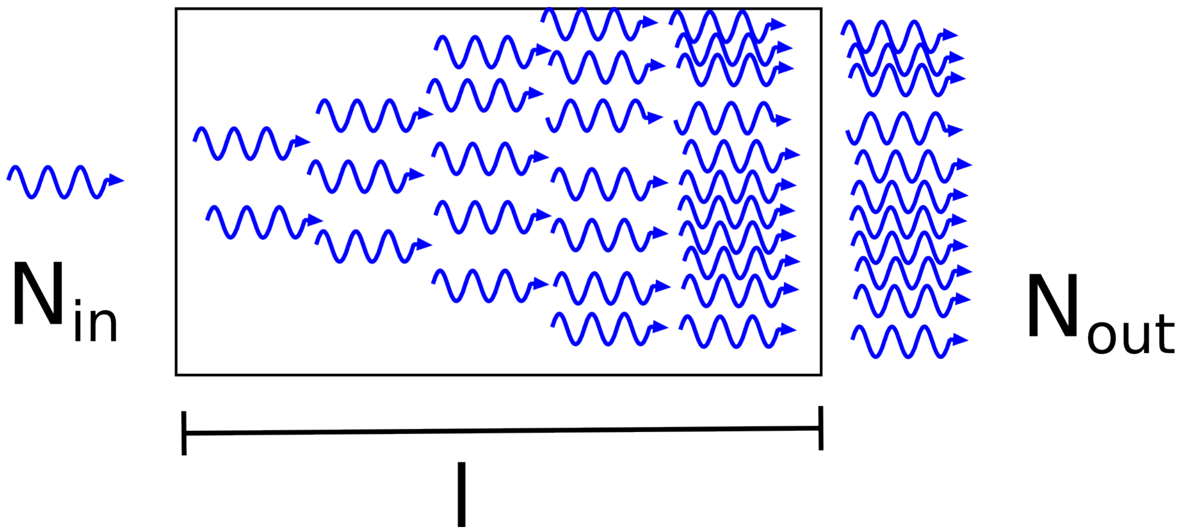






Laser diodes:
Net gain (g)

•The net gain of a material is a number which tells us how many photons we will get out of a 1 meter length of material if we put one photon in.

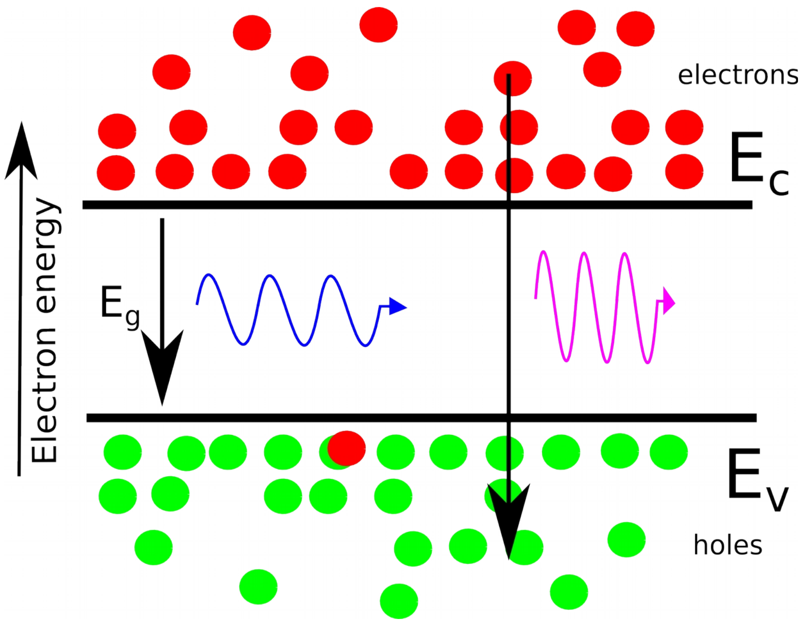


$$net\ gain = \frac{N_{out}}{N_{in}\, l}$$

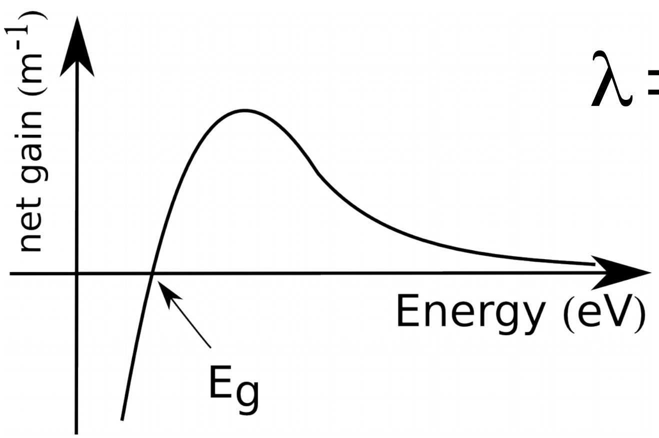
Where l is the length

What wavelength will our laser be?

- Not only do we have carriers distance Eg apart but we really have a distribution of carriers above and below Ec, Ev.



- This means that our photons can be emitted also over this distribution.

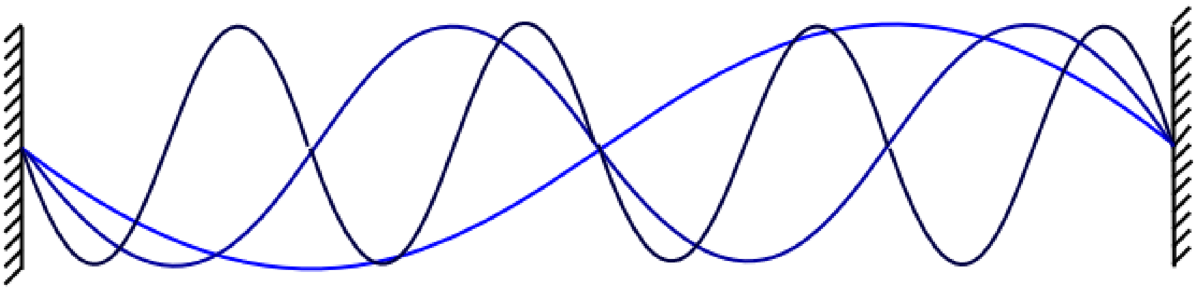


$$\lambda = \frac{hc}{Eg}$$

- The result is that our material can only produce gain over a certain region of the spectrum.

Let's look at what the mirrors do to our laser:
Optical resonant cavities

- Think of the strings on a Guitar.
- Only certain modes can be supported on the instrument:



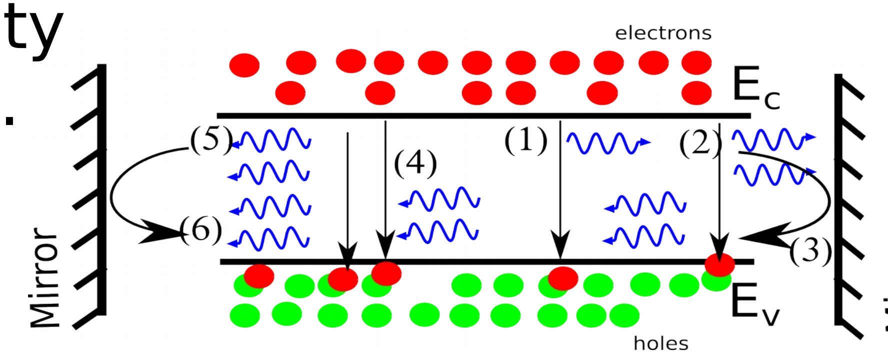
Martin Möller

- This means that only a set number of wavelengths can be supported by the cavity.

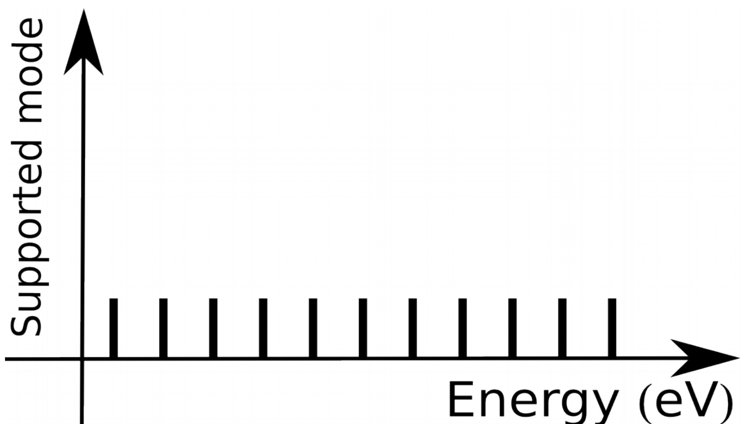
- It is the same for our laser cavity:

Optical resonant cavities.

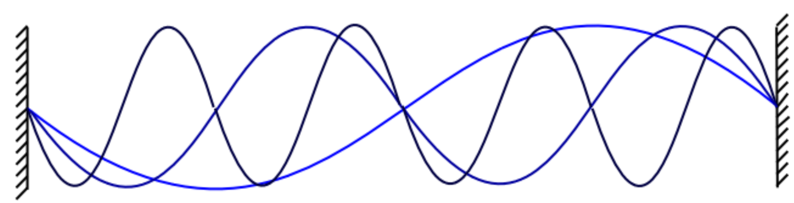
•This means that our laser cavity will only support certan modes.



Picture of laser cavity



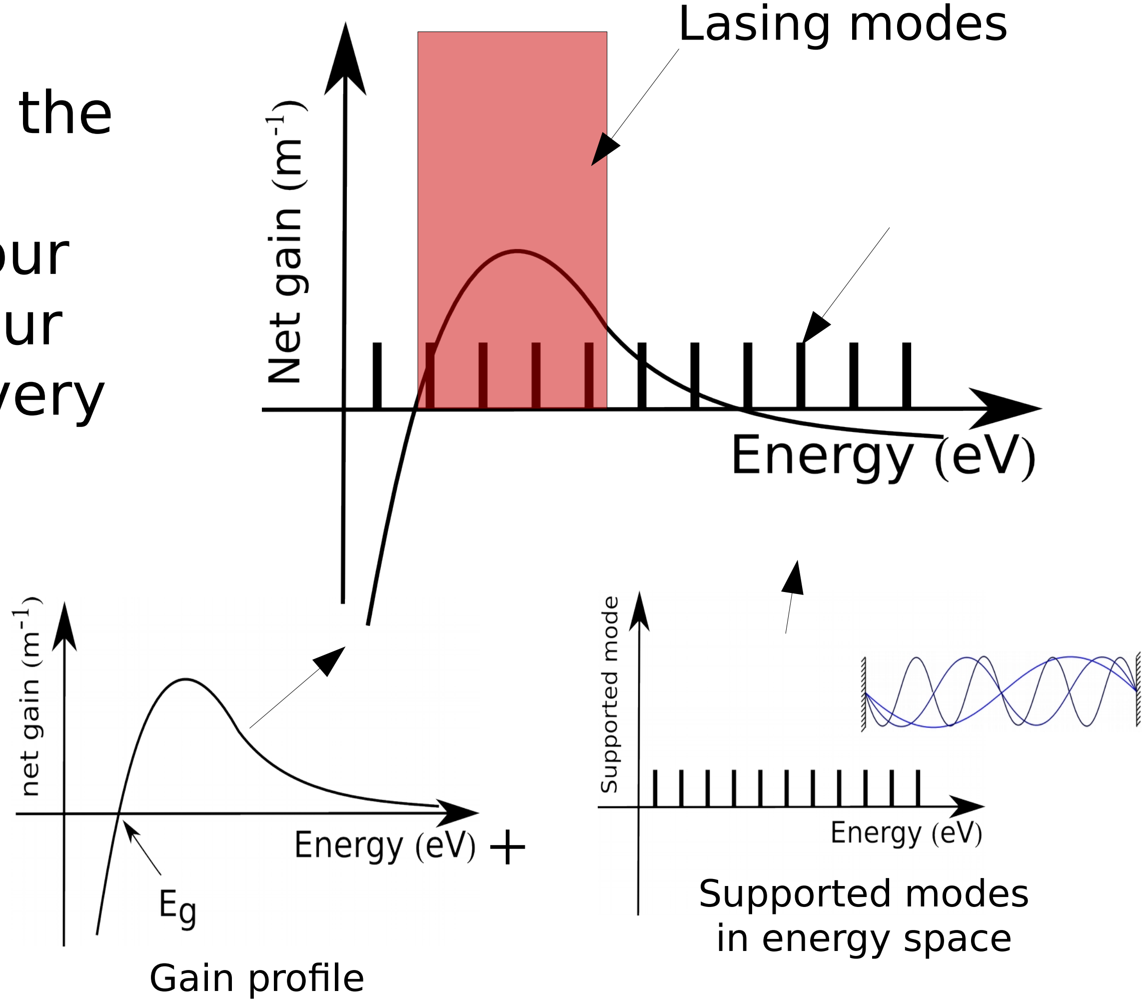
Supported modes
in energy space



Supported modes
within cavity

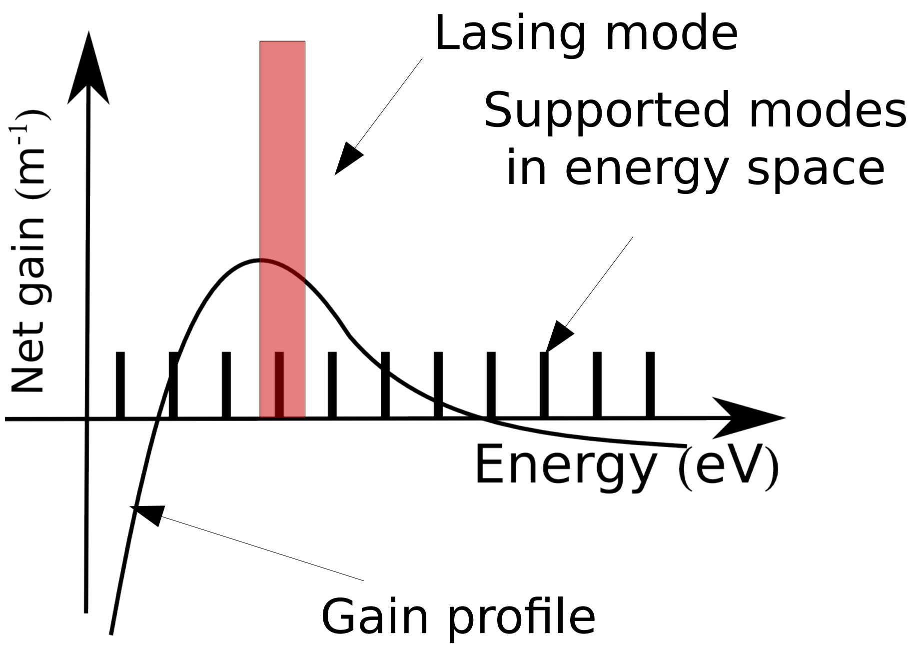
Optical resonant cavities with gain

Thus when we overlap the modes our cavity can support and the gain our material can provide our laser can only lase in very few modes.

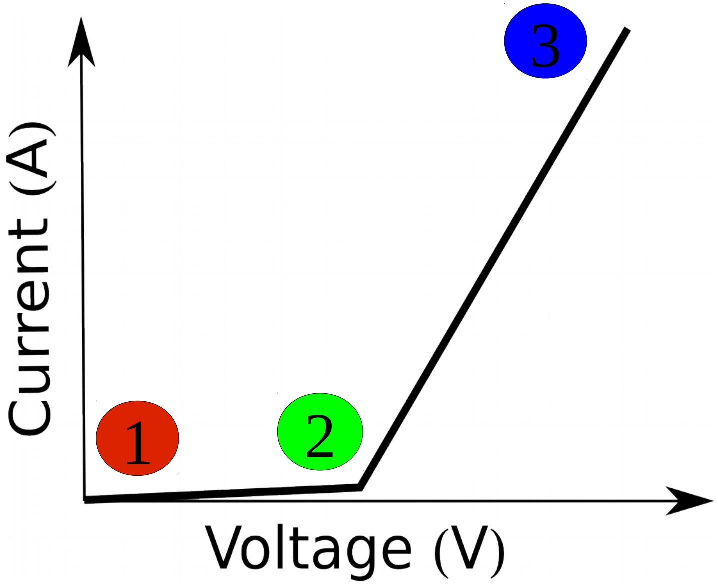


Single mode lasing

- Our laser will tend to lase in the mode with most gain.
- The material will produce most photons here. These photons will generate more stimulated emission and the process repeates.
- This is like puppies feeding. The bigger one always gets more food.



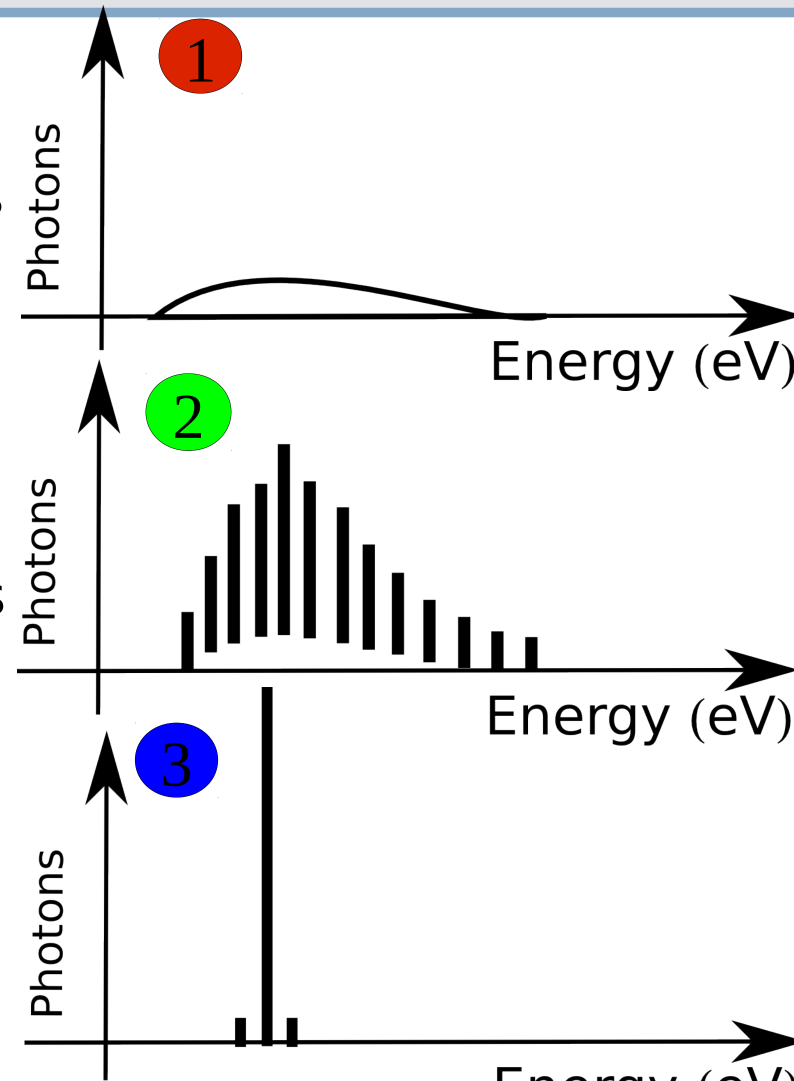
Laser emission below, just below and above threshold.



Below threshold spontaneous emission

Just below threshold amplified spontaneous emission

Above threshold



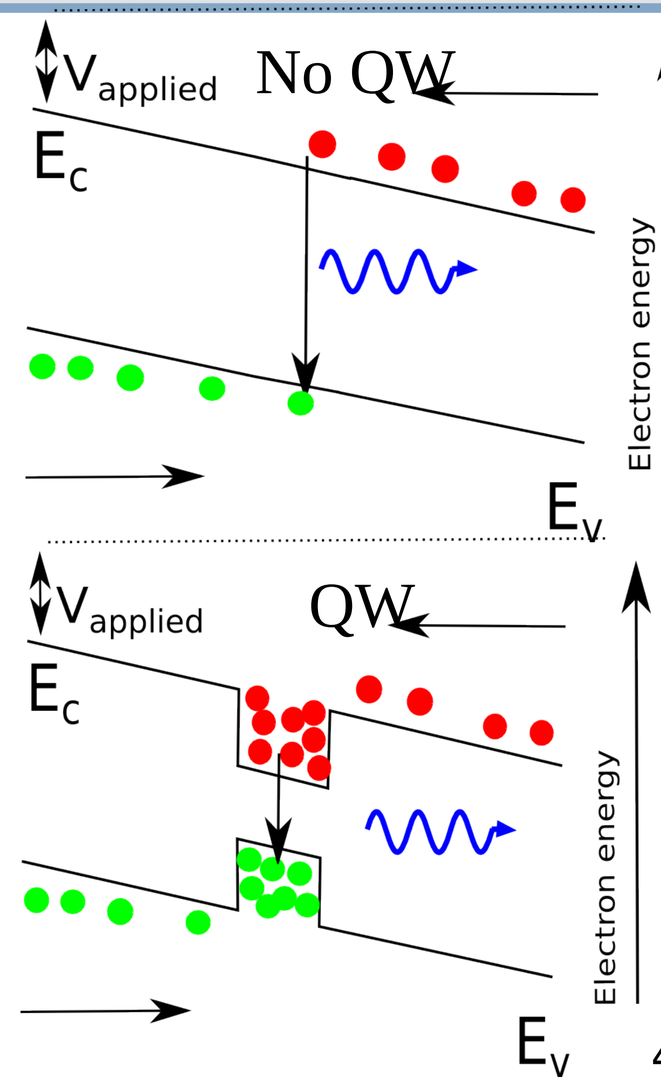
Making laser diodes more efficient

- The laser diode I described up until now was the original laser diode as fabricated in 1960.
- If you made it, it would have a very high threshold current (1000 A/cm2) and be very inefficient.
- It would also get very hot so you would have to cool it to 77 K.
- We therefore need an improved design

Making lasers better....

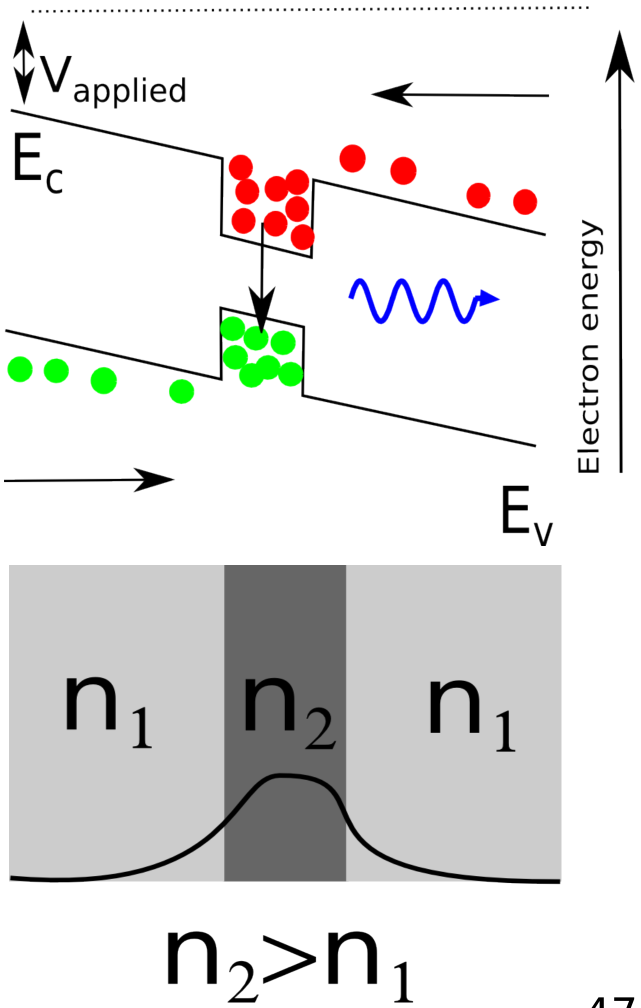
Confinement of carriers to reduce threshold

- To improve the efficiency of the laser we introduce a quantum well.
- This is a lower band gap material with a lower band gap than the bulk material.
- This means that carriers get trapped in the QW and get confined, increasing the current density and making it easier for the carriers to radiatively recombine.

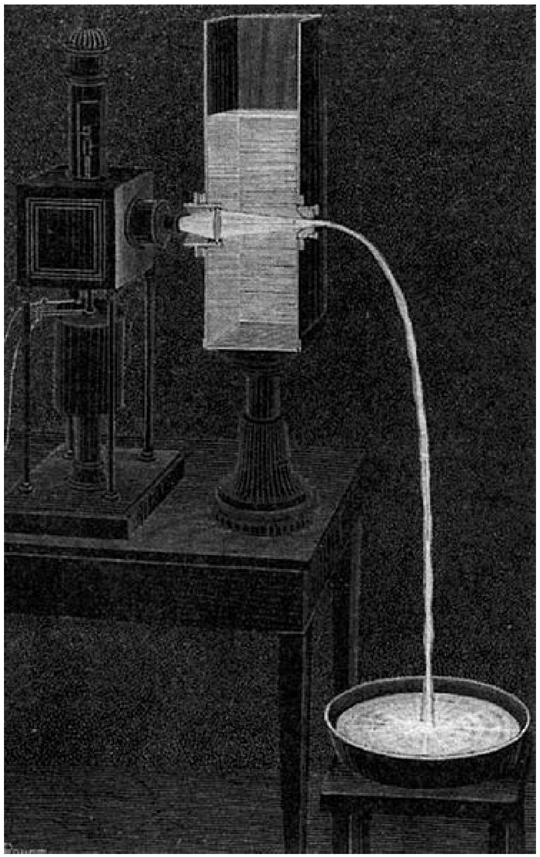


Making laser diodes more efficient

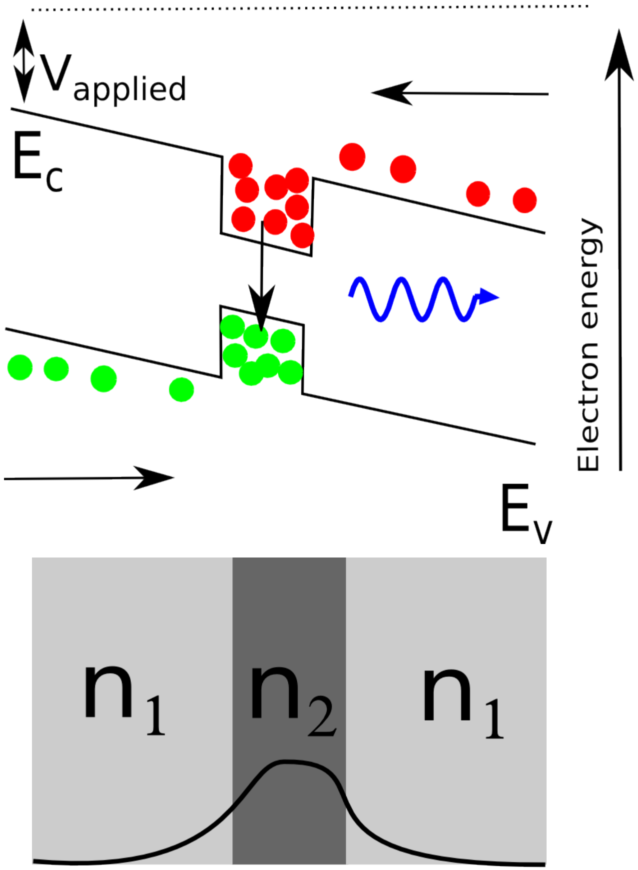
- The other advantages of quantum well lasers is that the material surrounding the quantum well can be made of material of a lower refractive index thus you also get optical confinement.
- This means more of the photons are kept in regions where there is net gain. (near the QW)



Optical confinement within the laser



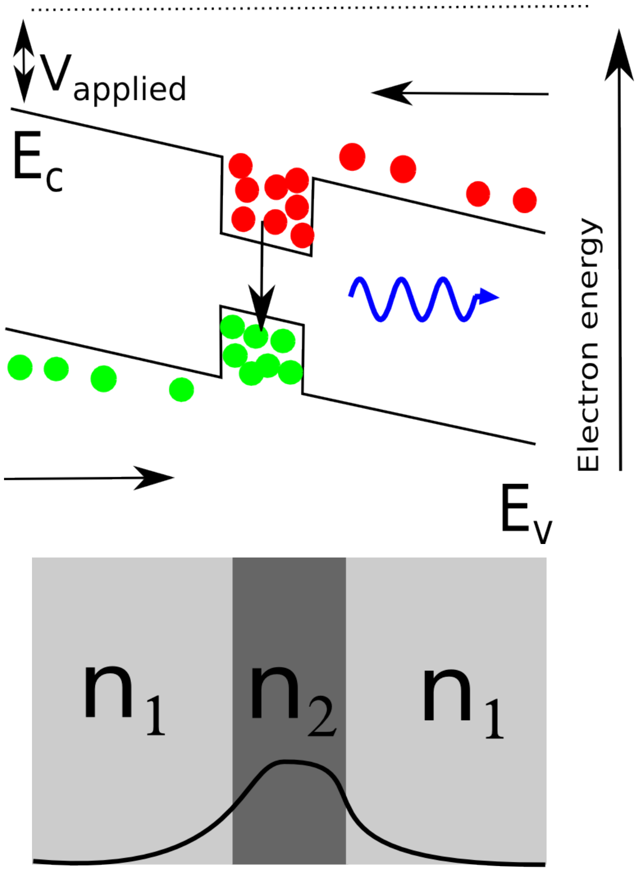
Water internally reflected



$n_2 > n_1$

Separating electrical confinement and optical confinement

- Ideally we would like our quantum well very thin to so it has a high carrier density.
- However this may not be desirable for the optical waveguiding properties of the laser.
- Therefore in modern lasers we introduce a separate optical confinement layer



$n_2 > n_1$

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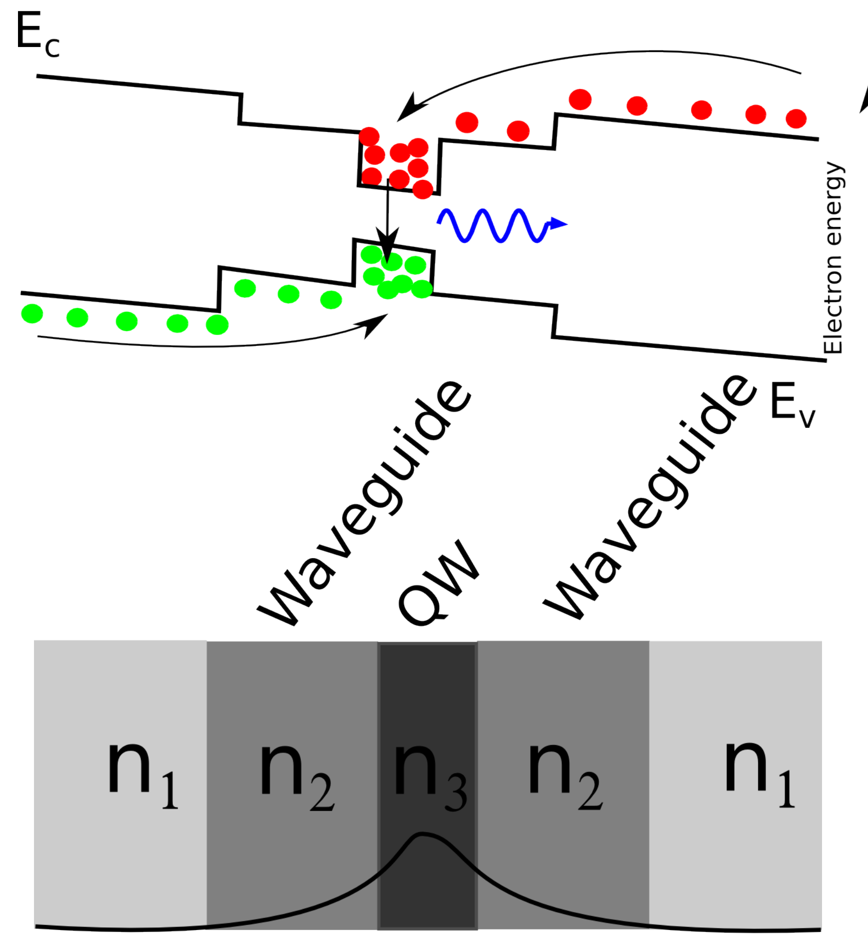
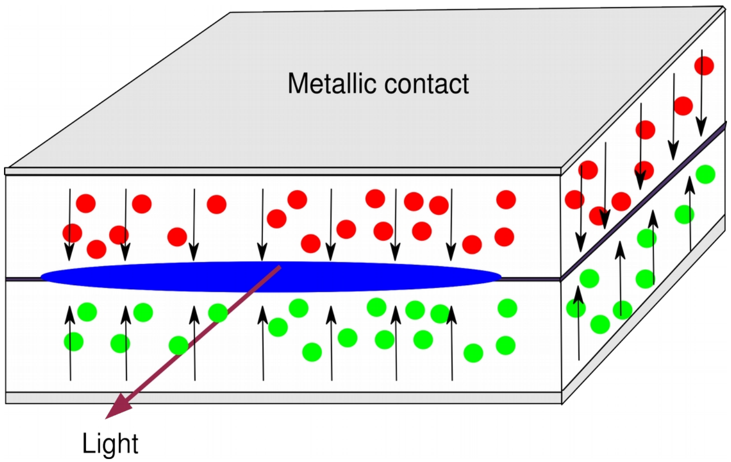
- Therefore in modern lasers we introduce a separate optical confinement layer

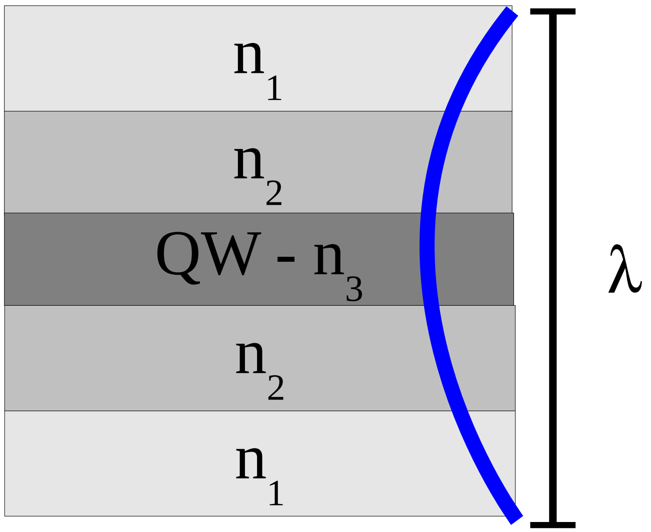


$n_3>n_2>n_1$

Broad area lasers

- So far our laser looks like a sandwich structure.
- We have electrical and optical confinement vertically but no confinement horizontally.
- This is called a **broad area laser**.
- It is used in high power applications – such as inter satellite communication.
- Typical output powers ~1W

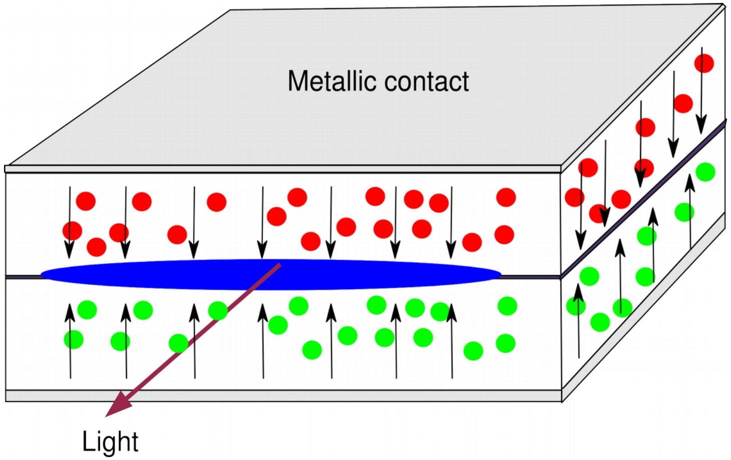


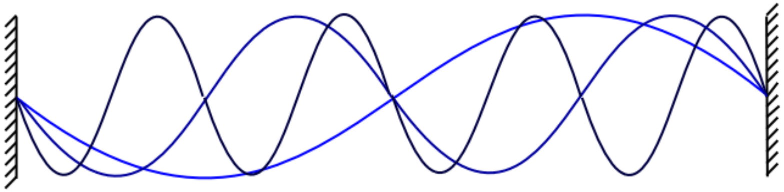


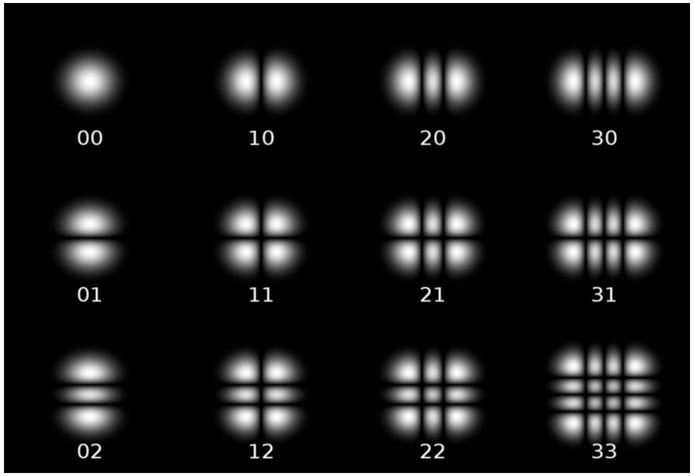
Broad area lasers are multimodal.

•Broad area lasers are typically multi modal. Meaning that lots of modes can be supported.

•This makes it difficult to couple the light into single mode fibers.



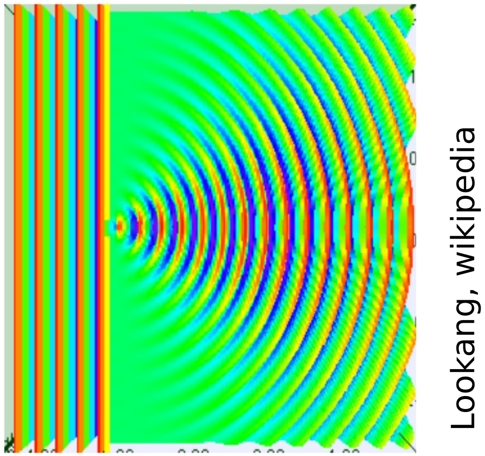




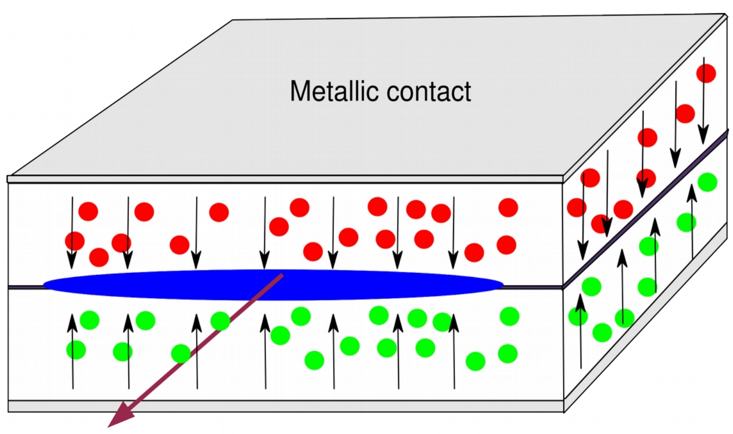
Broad area lasers have very asymmetric beams

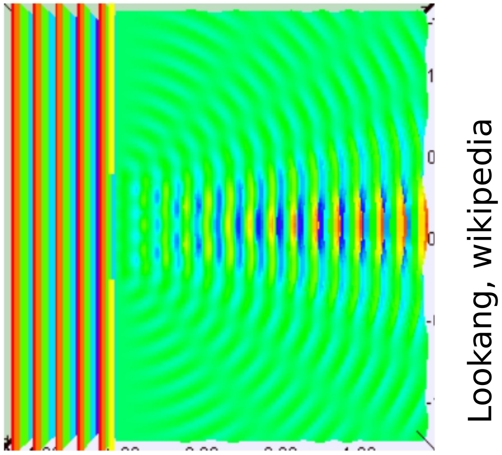
•Think of light diffracting through a very thin slit and light diffracting through a wide slit.

•The narrow slit will diffract the light more.



Narrow slit



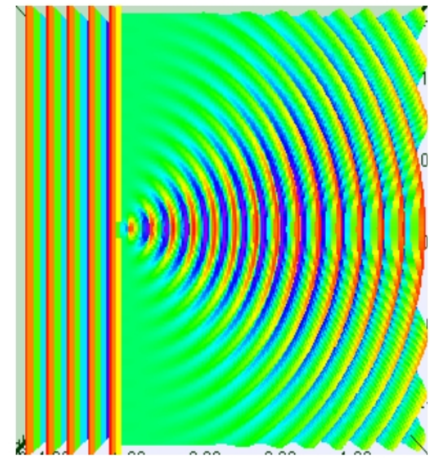


Wide

Broad area lasers have very asymmetric beams

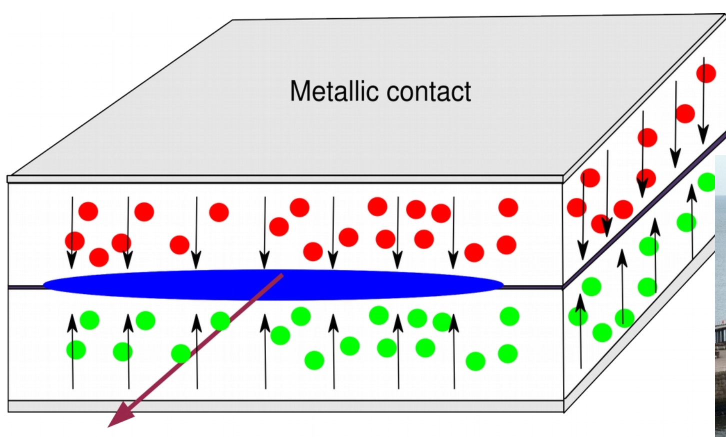
•Think of light diffracting through a very thin slit and light diffracting through a wide slit.

•The narrow slit will diffract the light more.

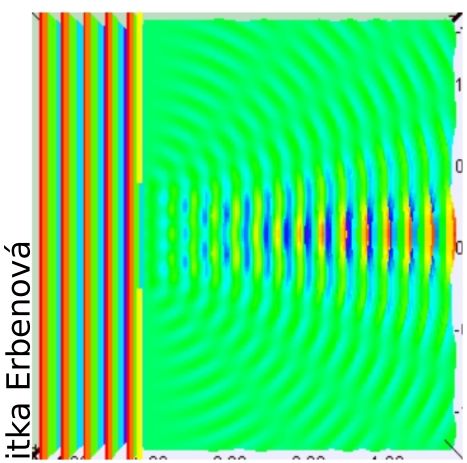


Lookang, wikipedia

Narrow slit



Jitka Erbenová



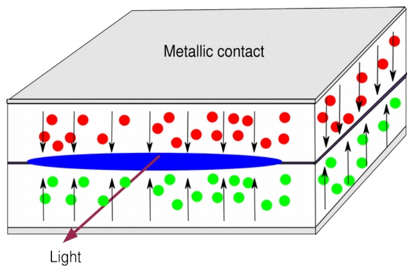
Lookang, wikipedia

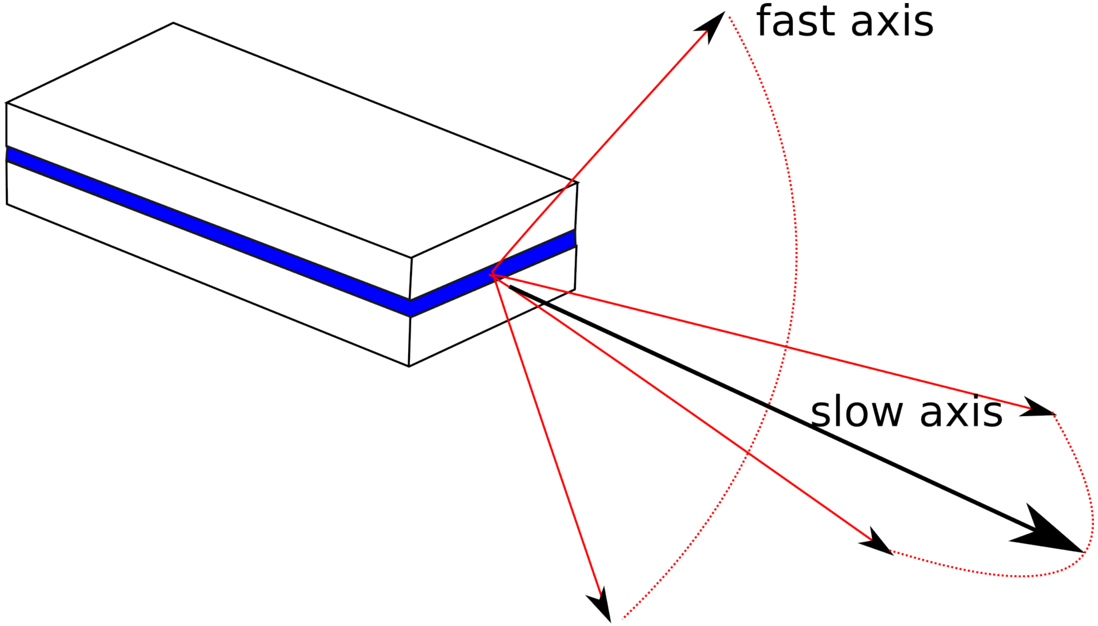
Wide

Broad area lasers have very asymmetric beams

•Our laser is just like this slit.

•This means that in one direction light will be very broad and in the other very narrow.

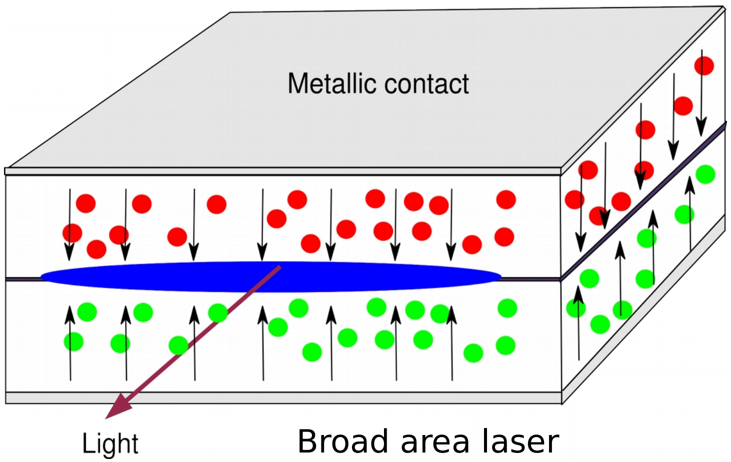




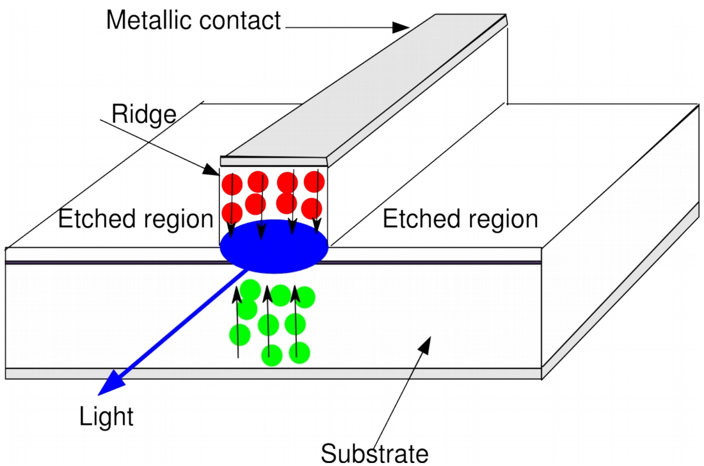
Making laser diodes more efficient: Ridge waveguide lasers

•However we often don't need 1W of power to send light down a fiber – we need 10mW at most.

•We often therefore etch away the sides of the laser to form a ridge waveguide laser to make the area smaller.



Broad area laser



Ridge waveguide laser

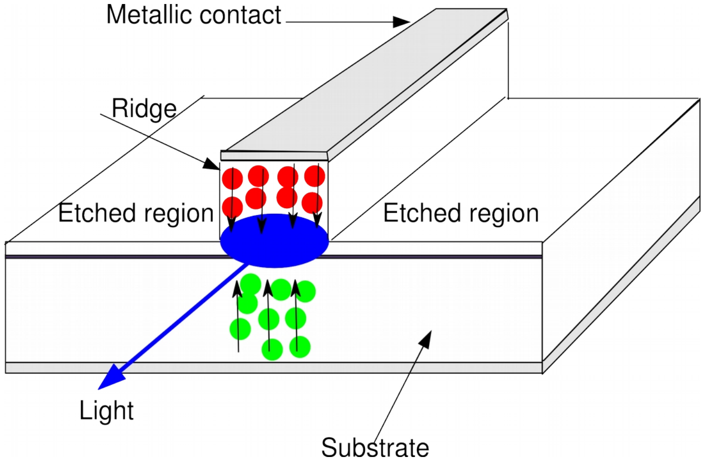
Ridge waveguide lasers

•Ridge waveguide lasers are well suited to telecoms applications

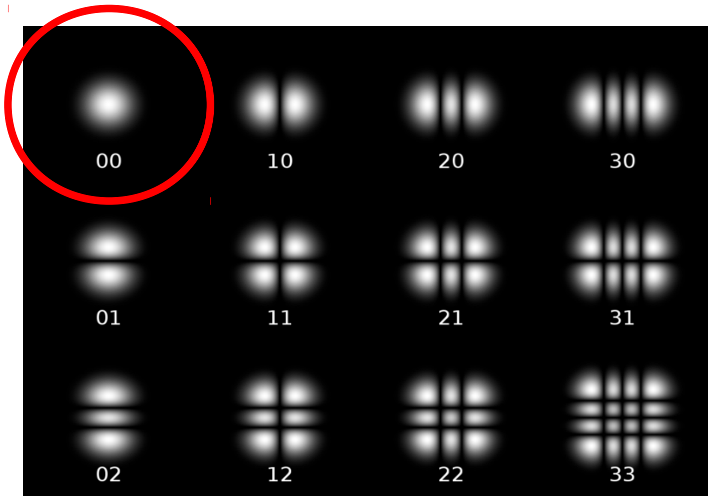
•Due to the small area they don't need much current to lase.

•They also have a low capacitance (small area) so they can be modulated quickly.

•RW lasers are typically single mode making the light that comes from them easy to link into fiber optics.

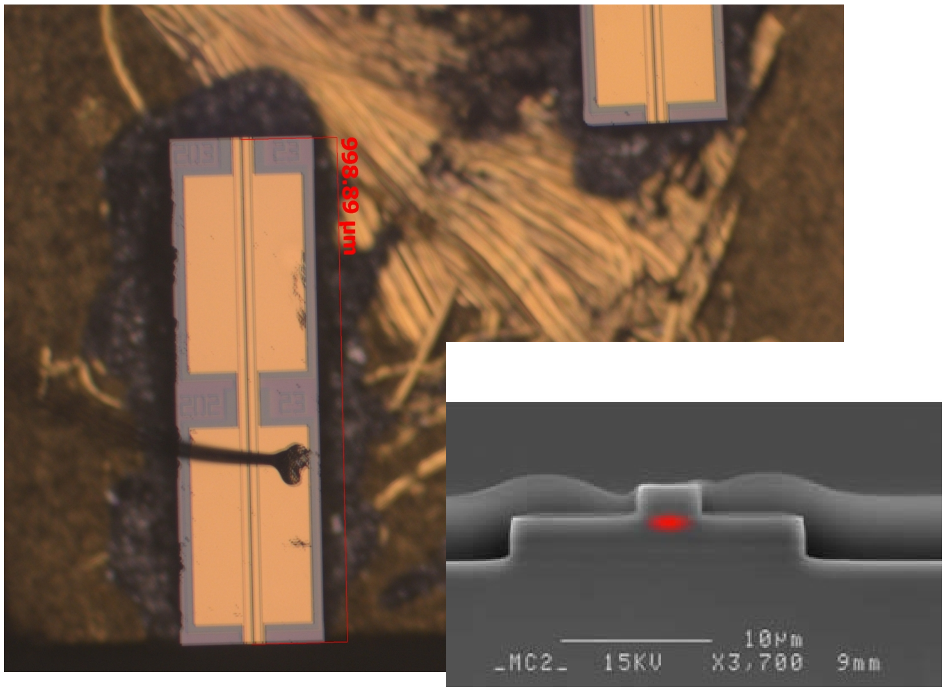


Ridge waveguide laser



DrBob at en.wikipedia

Ridge waveguide laser:
In practice



A SEM image of a laser diode
(fast access project)

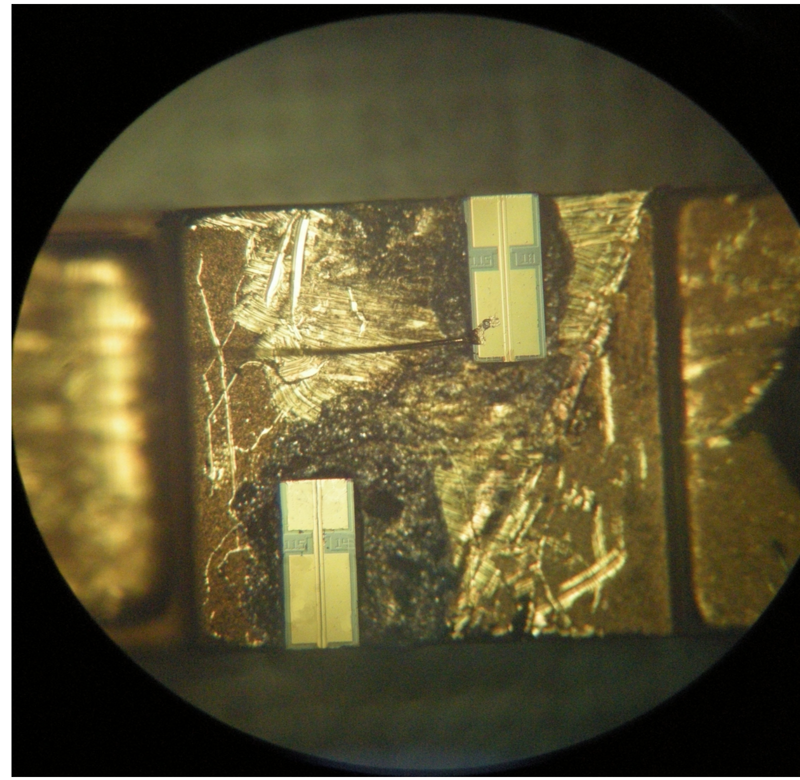
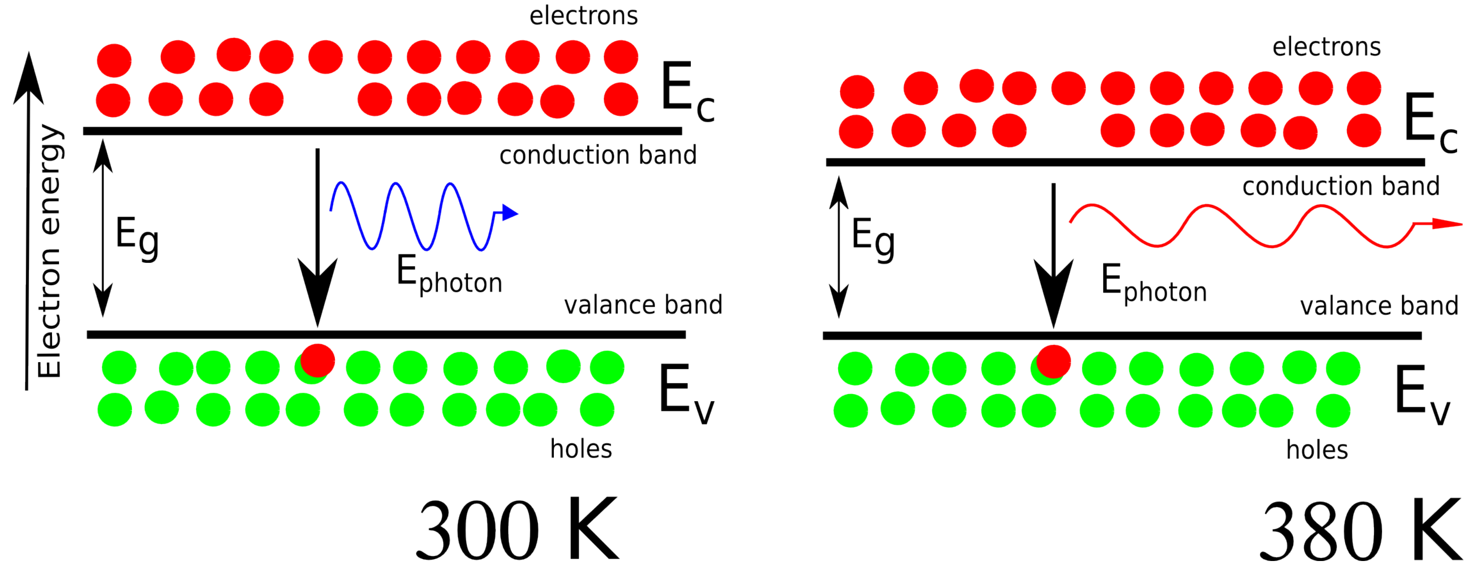


Image of the sub-mount and two lasers mounted p-side up. A bonding wire is visible connecting the uppermost laser diode to a contact pad visible in the left of the image.

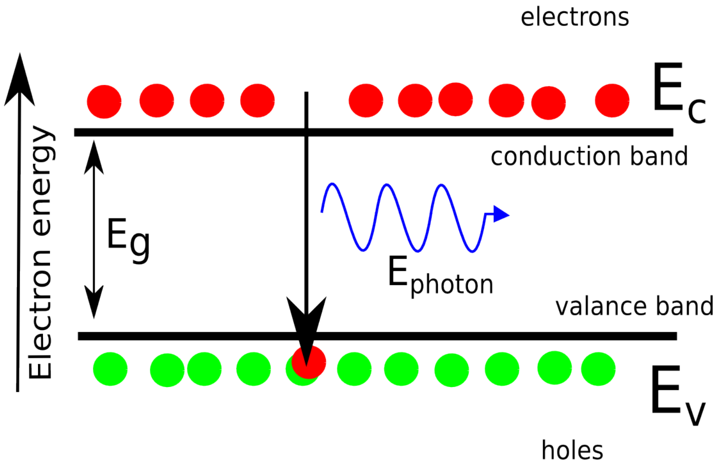
Difficulties with RW laser structures: Red red shifts due to heat

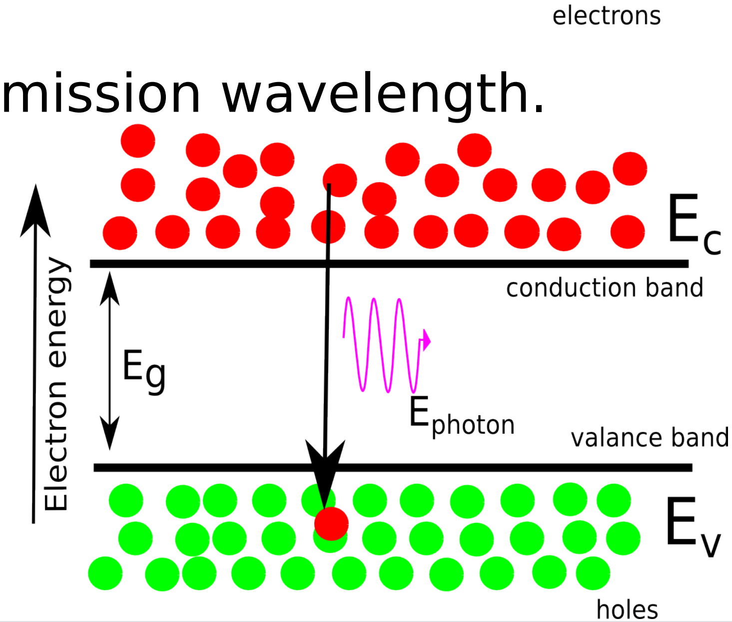
- As you heat a semiconductor the band gap shrinks
- This will mean your laser will red shift as the temperature increases.
- Not good for DWDM systems...



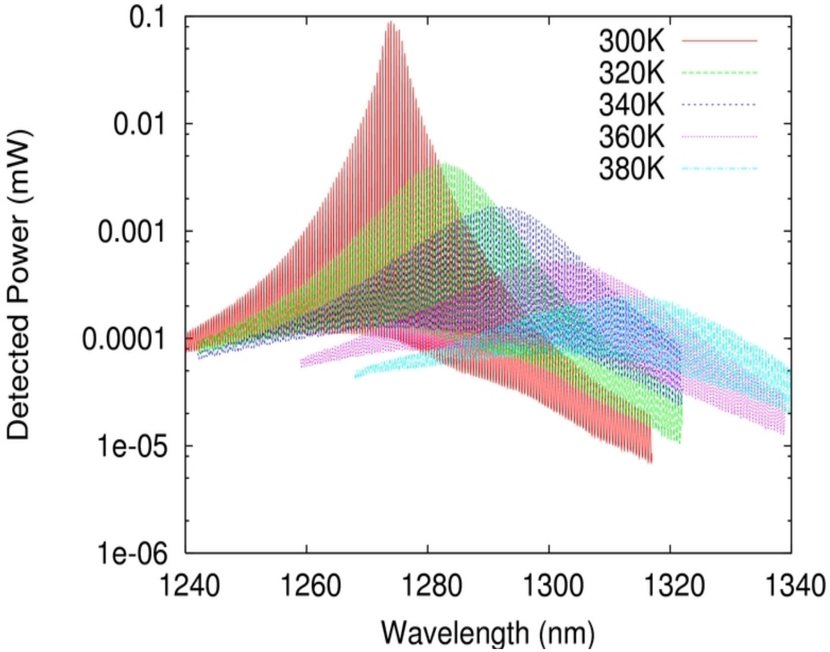
Difficulties with RW laser structures: Blue shifts due to carrier density

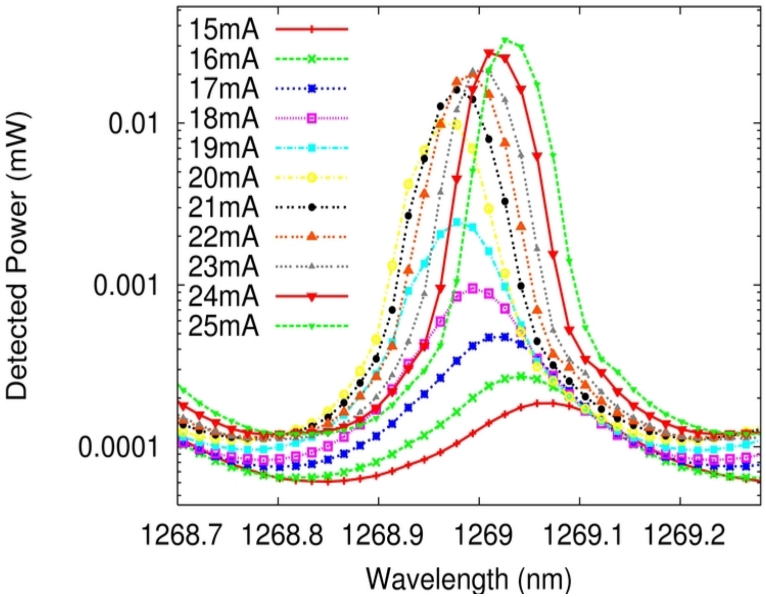
- At low carrier densiteis (low current), the carriers sit near the band edge.
- As current is increased there are more and more carriers.
- These are pushed higher and the average energy of the carrier increases.
- Thus there is a blue shift in the emission wavelength.





Ridge waveguide lasers
Red and blue shifts



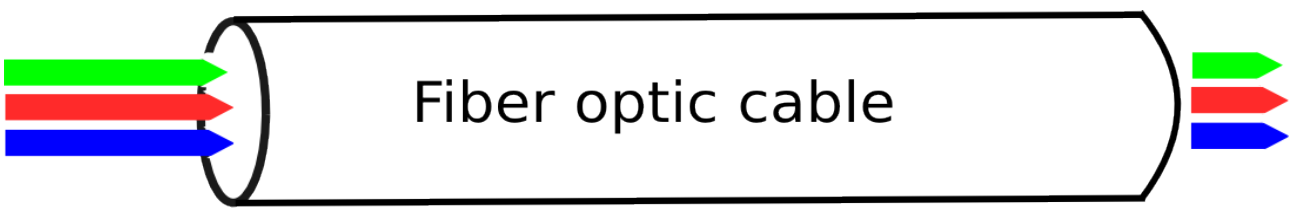


- Not so good for DWDM applications probably OK for fiber to the home.

Distributed feedback lasers (DFB) for DWDM systems

- Temicomunicaions systems need lasers which are very stable because you often want to send 20-30 wavelengths down a fiber, a shift of 60 nm in wavelength is unacceptable.

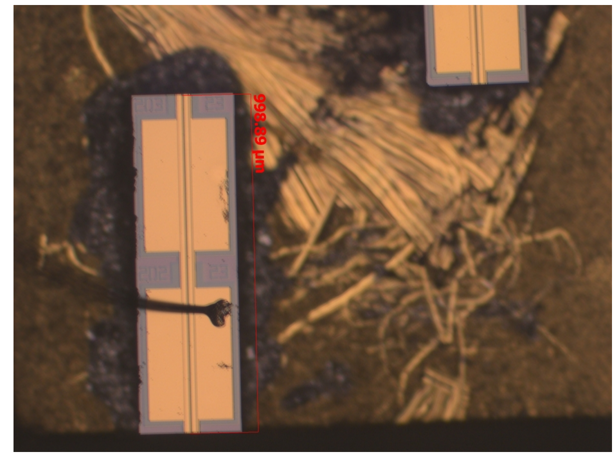
- How can we stabilize our laser's wavelength?



- Let's look at our laser again....

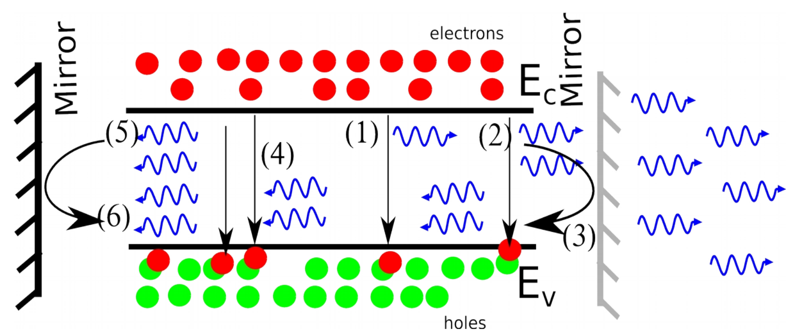
Distributed feedback lasers (DFB)

- In our laser so far the mirror on either end of the device was formed by simply using the air semiconductor interface.
- This mirror can reflect most wavelengths of visible light quite well.



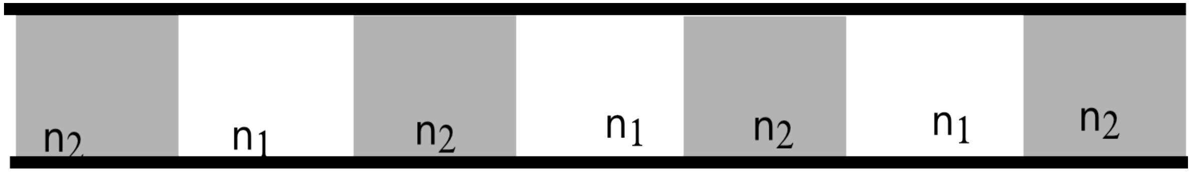
$$R=\left|\frac{n_2-n_1}{n_2+n_1}\right|$$

- What if we could make the mirrors only reflect one wavelength of light.
- Then our lasing wavelength would be set



Brag reflectors

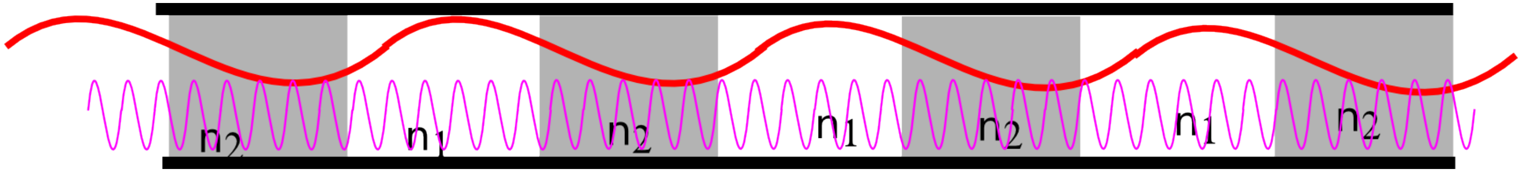
- Think about a periodic structure made of regions of high refractive index and regions of low refractive index.
- Light incident upon the structure will be reflected off the multiple interfaces.



$n_2 > n_1$

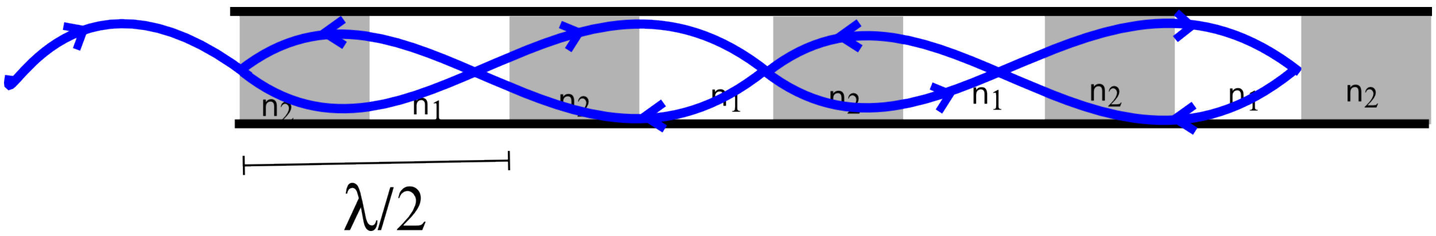
Distributed feedback lasers (DFB)

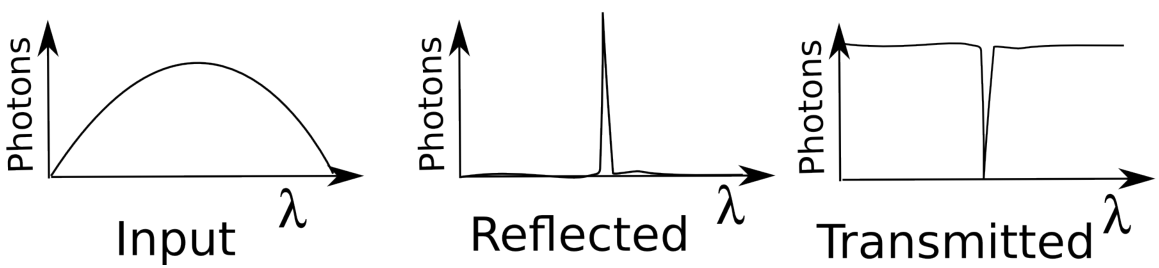
• Most light will scatter off the interfaces multiple times and pass through the structure.



Distributed feedback lasers (DFB)

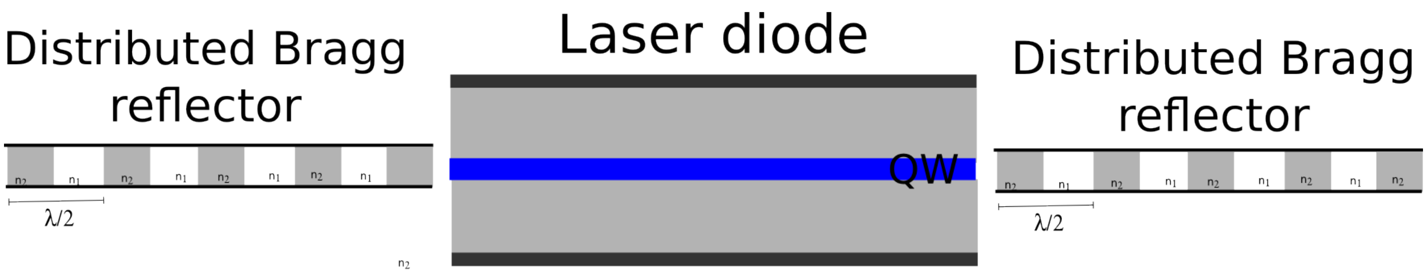
•However if the wavelength of light is exactly twice the period the light will be perfectly reflected.

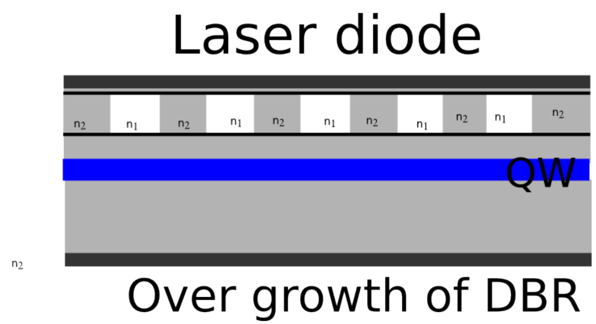




Distributed feedback lasers (DFB)

•By integrating these reflectors into the laser structure you can force your laser to be resonant at one wavelength.





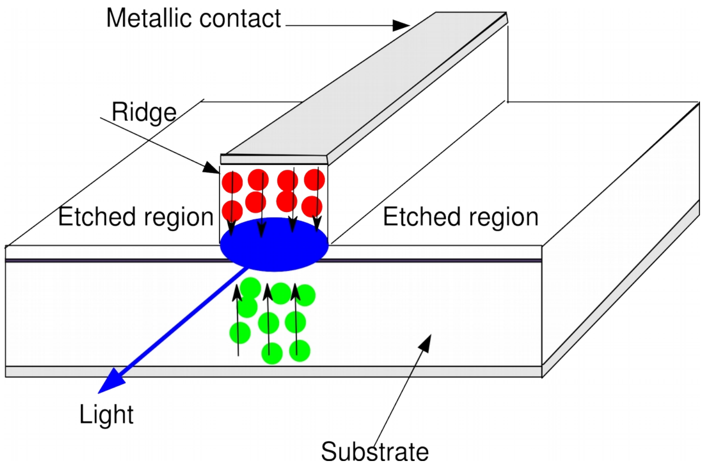
Edge emitting lasers

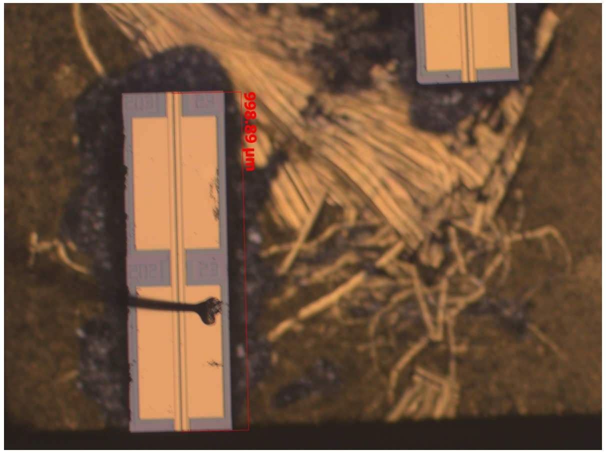
•All the lasers discussed so far are called edge emitting lasers.

•This is because they emit light from the edge of the substrate.

•The main disadvantage of these lasers is that the light is emitted from a very small region.

•This means the light is very divergent.



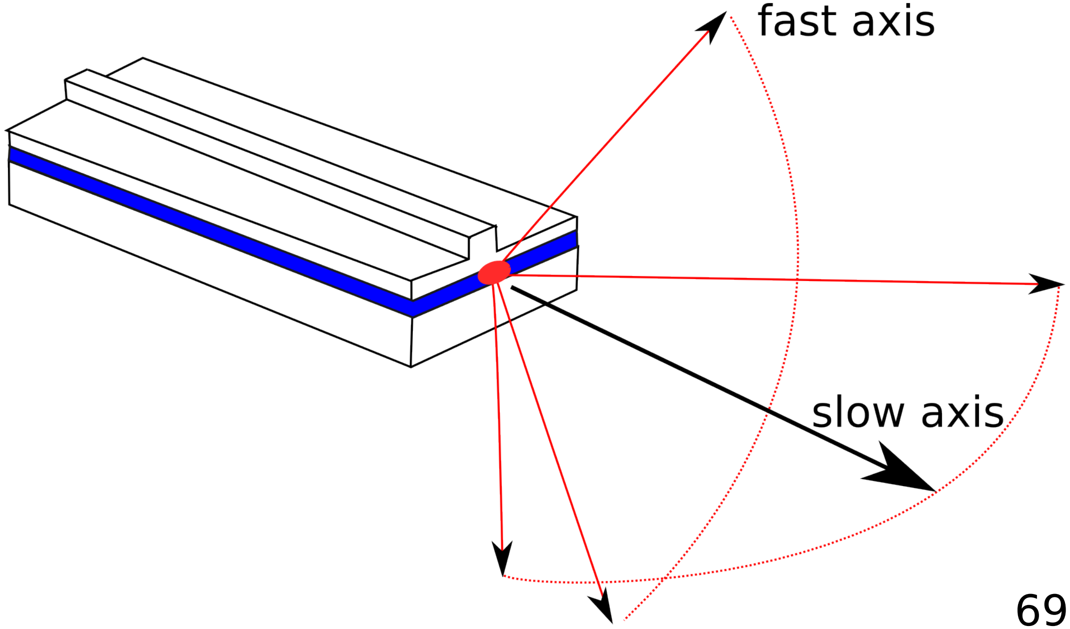


Edge emitting lasers

•Because the light is emitted from a small hole, it is very divergent.

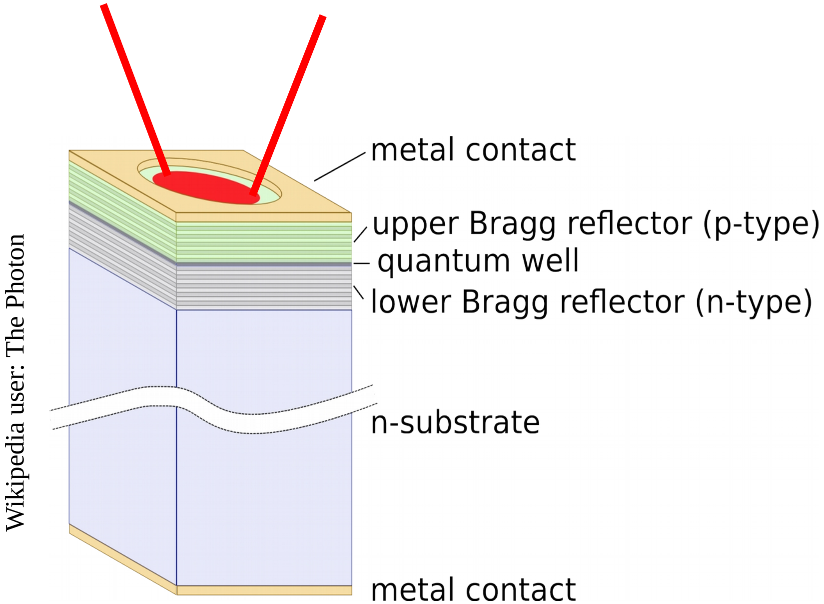
•This means that you often need a lens to couple the light into a fiber.

•This increases total system cost.

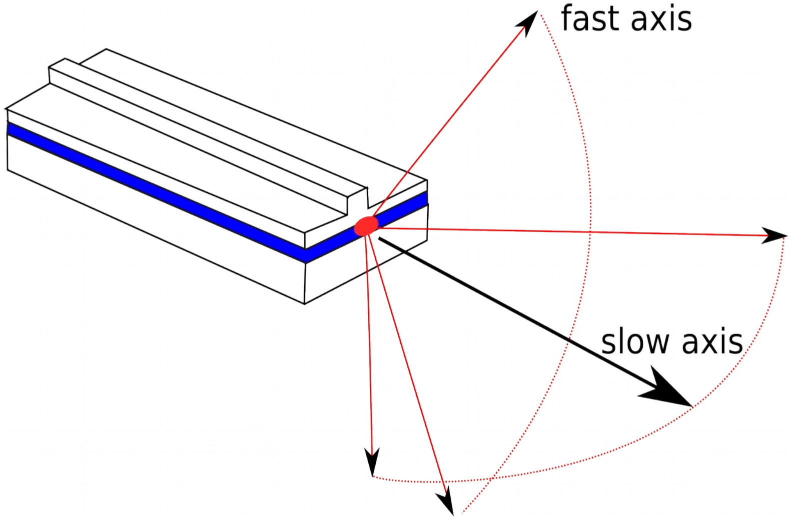


Vertical-cavity surface-emitting laser (VCSEL)

- This class of lasers was developed in 1980s.
- Instead of emitting from the side of the substrate, they emit from the top surface

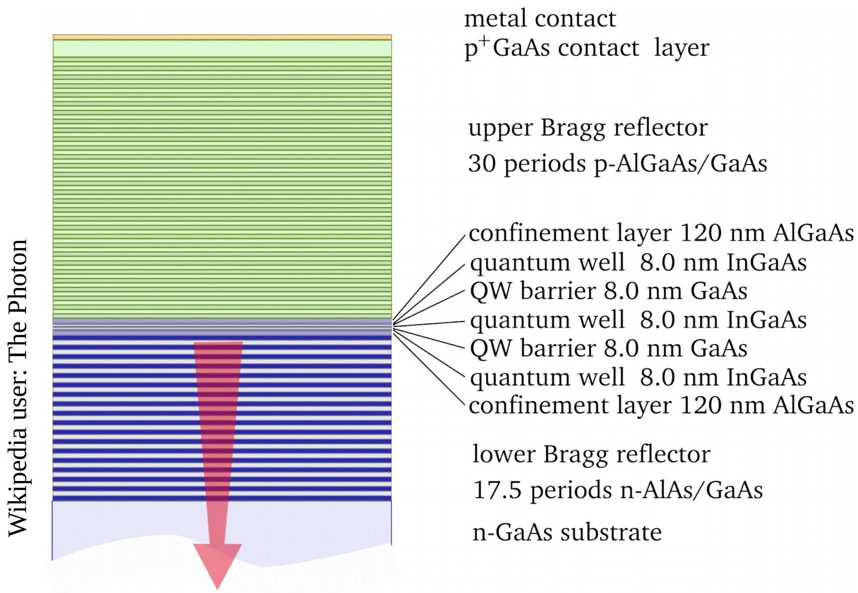


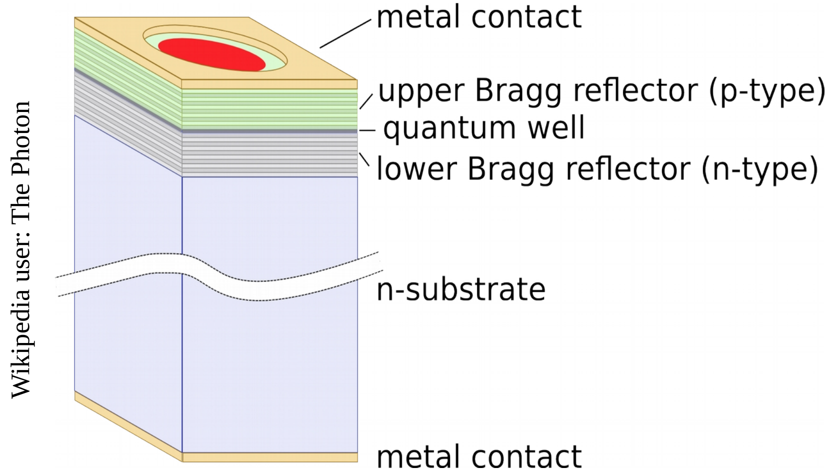
VCSEL



Vertical-cavity surface-emitting laser (VCSEL)

- The VCSEL's laser cavity is constructed from two brag reflectors one on top and one on the bottom.

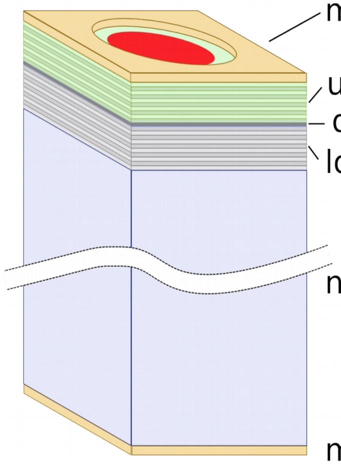




Advantages of the VCSEL

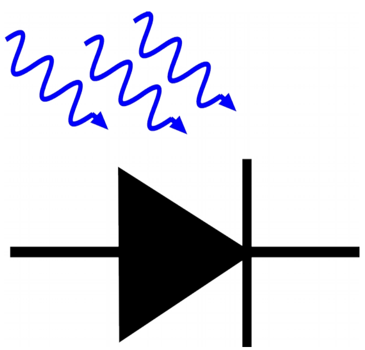
- Because the emitter area is wider there is less beam divergance.
- This makes the light easier to couple into fibers.
- No lens is needed for the coupling thus reducing the cost.
- All the advantages of a DFB laser

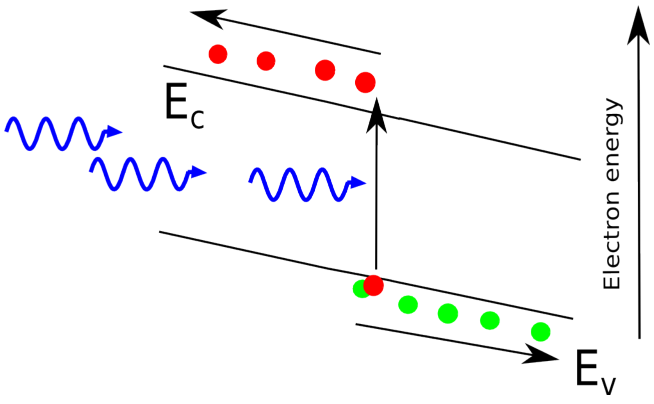
Wikipedia user: The Photon



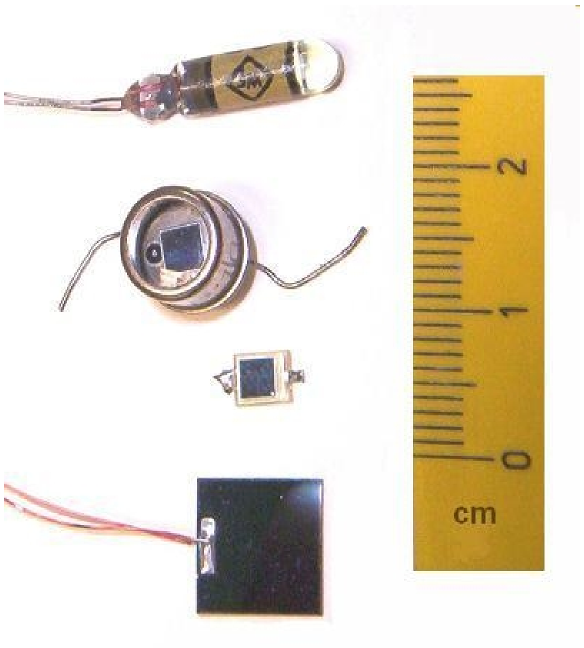
Photodetectors:
Fundamentals of operation

- So far we have looked at photon sources. I.e. the devices needed to generate photons.
- However to make any optical communication system we need photon detectors.
- The most simple photon detector is simply a diode which absorbs light.
- You can think of it as an LED in reverse





Photodetectors:
In general

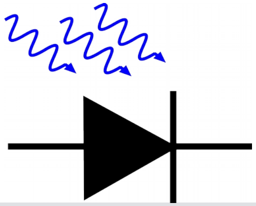


Ulfbastel Wikipedia (de)

Small photo diodes

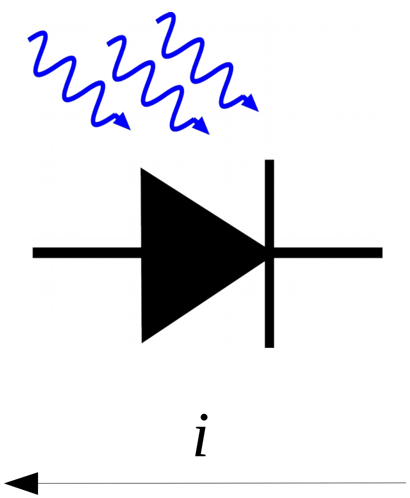
(image: Chinneeb, wikipedia)

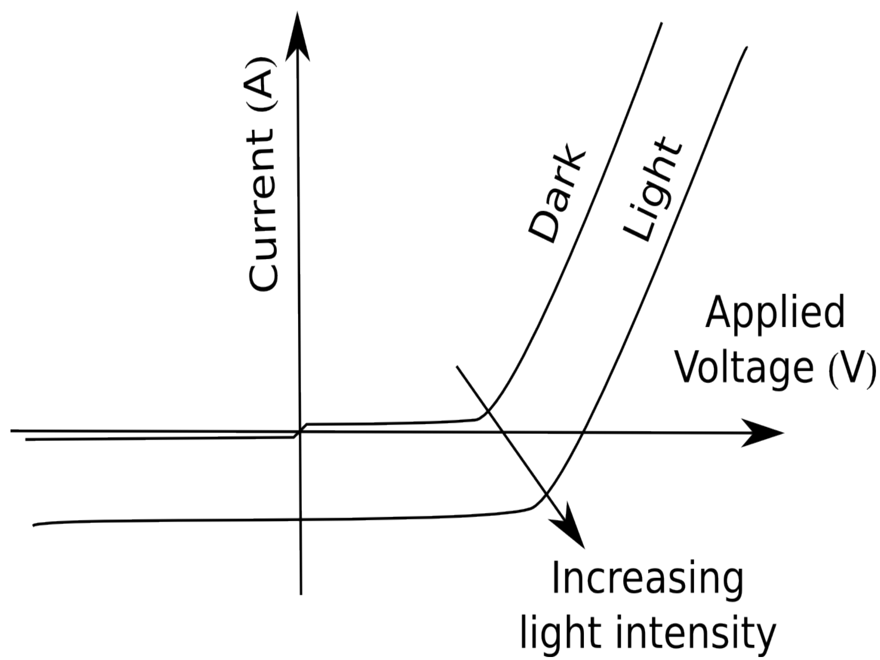
Large photodiodes,



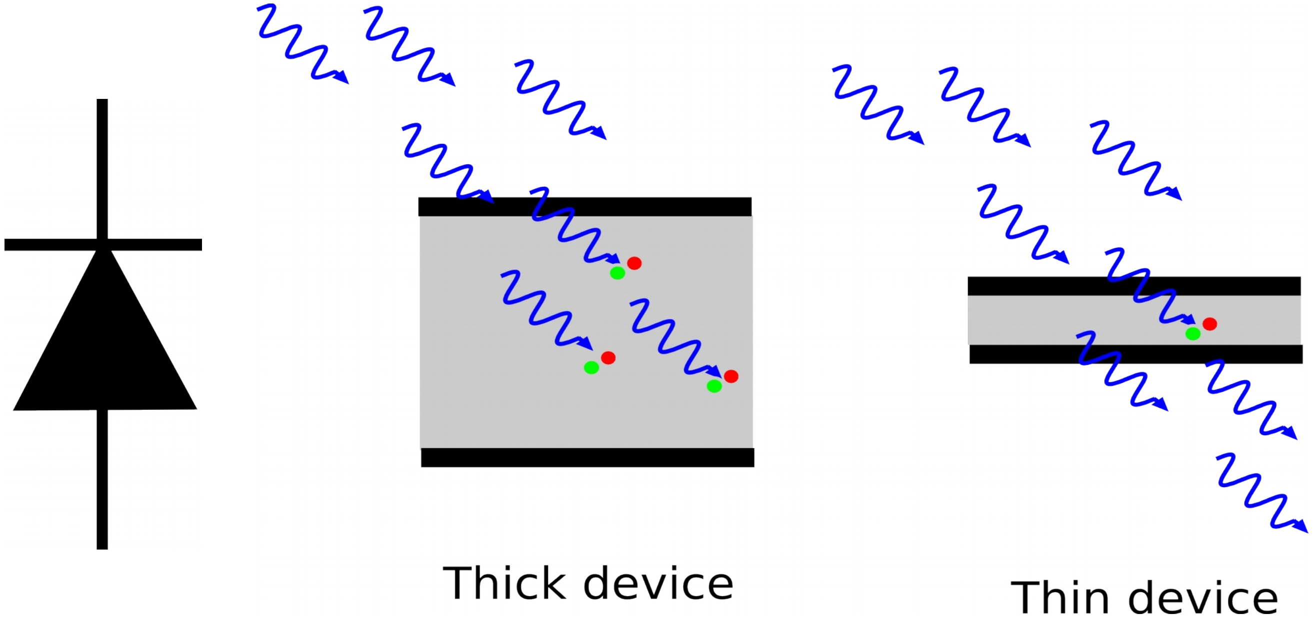
Photodetectors:
Fundamentals of opperation

- Because our device is generating current the IV goes negative.
- This means current is flowing out of our device rather than into it.



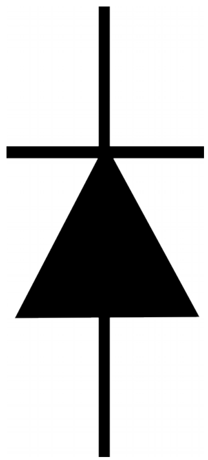


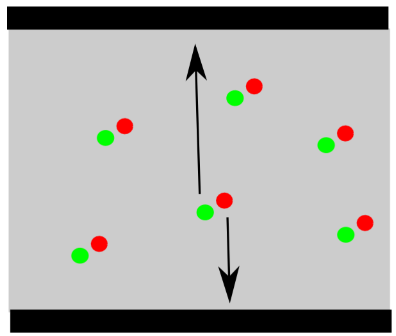
Photodetectors: Design considerations



•If you make the device very thick it will have a high gain. (lots of photons will be absorbed)

Photodetectors
design considerations





Thick device
Slow transport
to contact

Thin device
fast transport
to contact

- However a thicker device will have a slow response time.
- Meaning that it will not be able to detect very fast signals.

Photodetectors: figure of merit.

- The are two key figures of merit for a photodetector.
  - The gain (i.e. how sensitive it is to very weak signals)
  - The noise.
- Therefore a good figure of merit is the gain noise product.

Figure of merit=gain*bandwidth

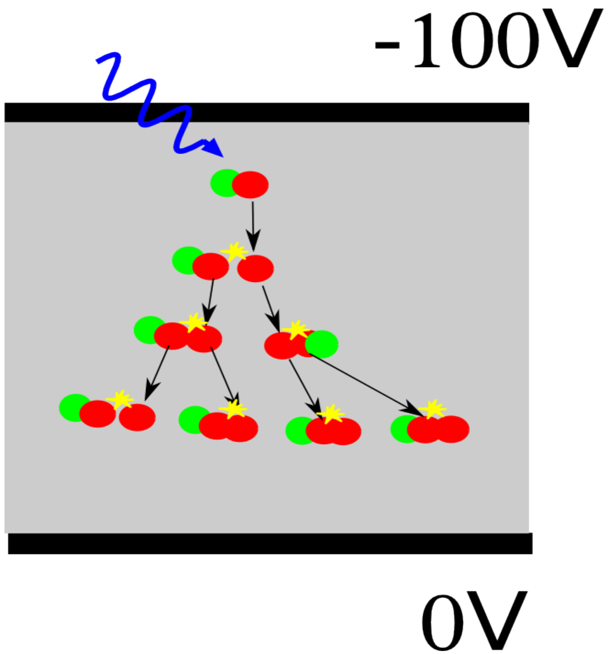
- Designs with high gain tend to have a slower response.

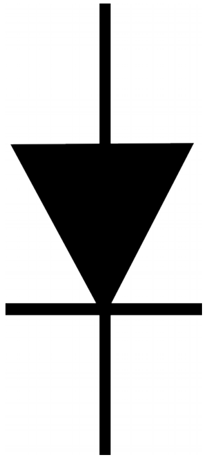
Photodetectors with gain.

- The photodiodes discussed so far always have a gain <1 because there is no amplification of the carriers.
- There is another type of photodetector called an avalanche photodetector which can provide give you more than one electron for every photon you put in.
- These are typically made of silicon.
- A very high negative bias is applied to the device the result is....

Photodetectors with gain:
Avalanche photodiode

- You can think of an avalanche photodiode as a diode with a built in amplification.
- This will bring a very weak signal above the detection level of your electronics.

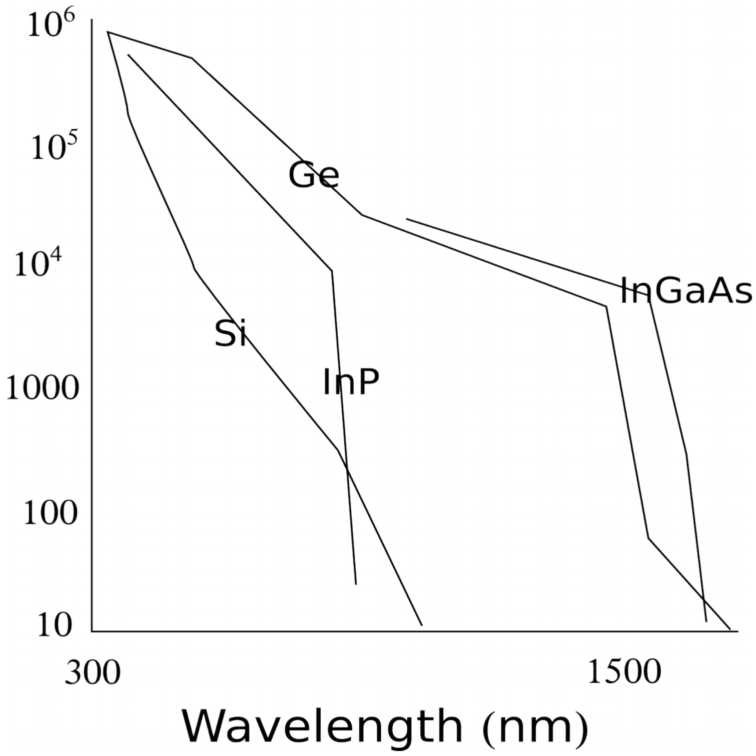




Gain > 1

Photodetectors: material choice

- Finally, when choosing a photodetector you should remember that different materials absorb light at different wavelengths.



Summary

- In this lecture we have covered:
    - The basic operating principles of edge emitting laser diodes.
    - The advantages of VCSLEs
    - Photodetectors

http://www.roderickmackenzie.eu/lecturenotes.html