EEE337 Semiconductor Electronics
EEE348 Electronics and Devices
(LASERS)

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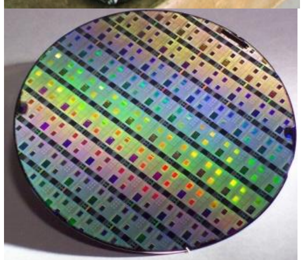
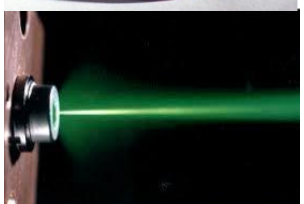
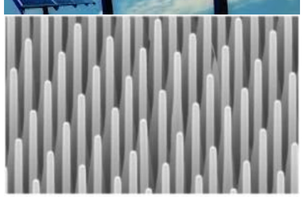
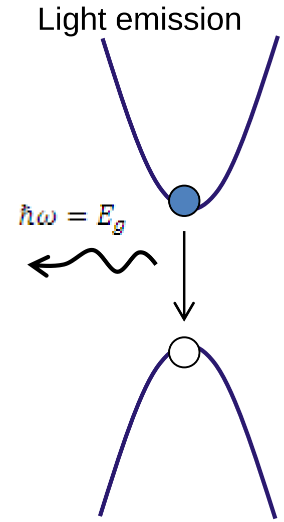
Light emission







1 µm

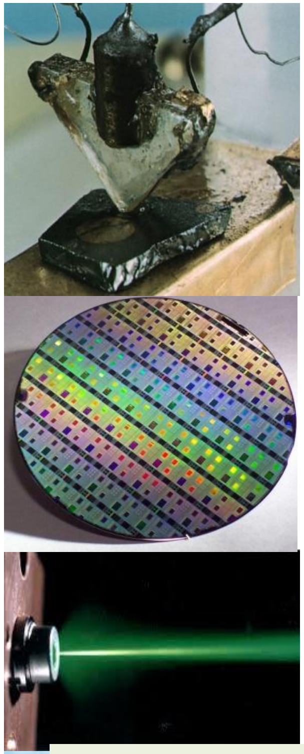


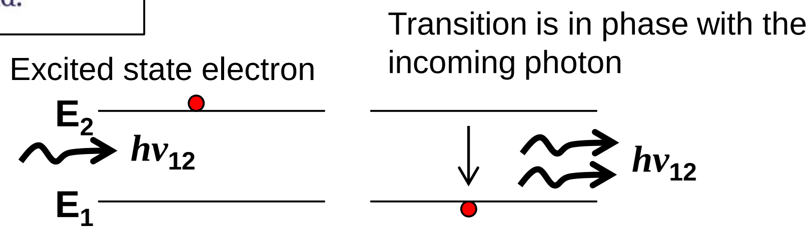
When an electron from the conduction band recombines with a hole in the valence band, a photon with energy very close to the bandgap E_g is emitted in a radiative recombination. Since conservation of energy and momentum is necessary the direct bandgap material has a much higher radiative recombination rate than an indirect bandgap material.

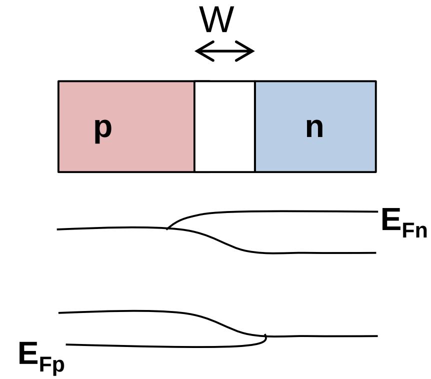
The simplest structure to achieve light emission is a forward biased homojunction pn junction. Not surprisingly this refers to the light emitting diode (LED), which is very attractive for display and low speed optical communication. The emission wavelength of LED is relatively broad and its modulation speed is limited. Hence **Light Amplification Stimulated Emission of Radiation (LASER) is used when wavelength selectivity and modulation speed are important such as in high speed optical communication.**

To achieve radiative recombination high concentrations of electrons and holes are required. By forward biasing the LED (or LASER) high concentrations of electrons and holes can be injected into the active region.

Stimulated emission

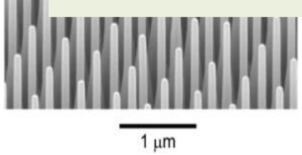


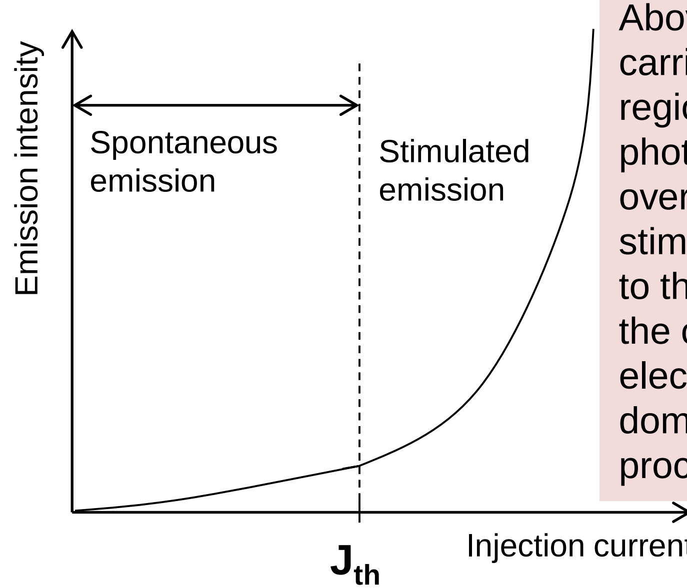




The conditions required to achieve stimulated emission are high photon density and high electron density in the conduction band (and high hole density in the valence band). The latter condition is known as population inversion and this is achieved when the injection current is high. The doping should be high enough such that the Fermi level E_{Fp} should be below the valence band in the p-layer and E_{Fn} should be above the conduction band in the n layer. A condition to achieve population inversion is $E_{Fn} - E_{Fp} > E_g$.

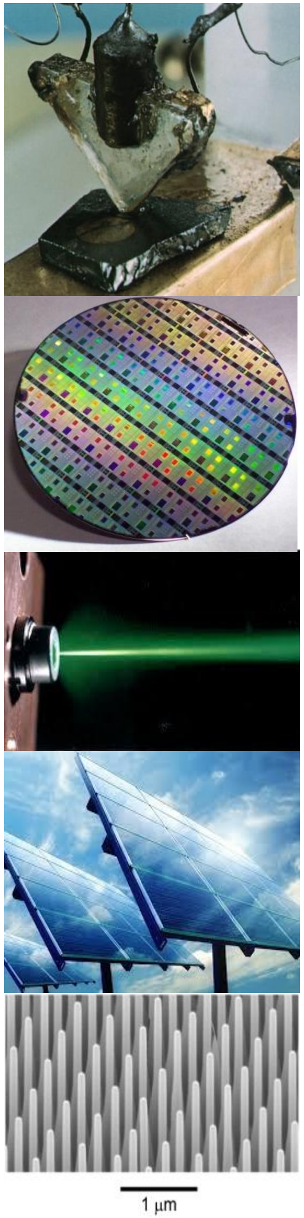
When the injected current is below the threshold current electrons and holes recombine spontaneously. Most of these photons are reabsorbed (a small number leaves the diode). Hence this is a loss mechanism.





Above the threshold current, more carriers are injected into the active region such that the number of photons increases (gain) to overcome the laser loss. Since the stimulated emission is proportional to the photon density (photons with the correct energy to cause the electron-hole transition), it dominates the recombination process.

Population inversion



The probability of finding an electron at an energy E is $$f^e(E) = \frac{1}{\exp\left(\frac{E - E_{Fn}}{kT}\right) + 1}$$

The probability of finding a hole at an energy E is $$f^h(E) = \frac{1}{\exp\left(\frac{E_{Fp} - E}{kT}\right) + 1}$$

The optical wave has an intensity described by $$I_{opt} = I_{opt_0} \exp\big(g(h\nu)x\big)$$

If $g(h\nu)$ is positive the intensity grows because photons are added by stimulated emission. To achieve this positive gain factor, population inversion is needed. The population inversion occurs when

$$f^e(E^e) + f^h(E^h) > 1$$

It can be shown that for GaAs the gain factor is given by

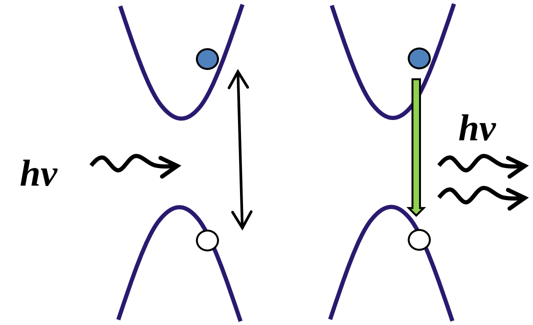
$$g(h\nu) = G_{las}[\, f^e(E^e) + f^h(E^h) - 1] \qquad cm^{-1}$$

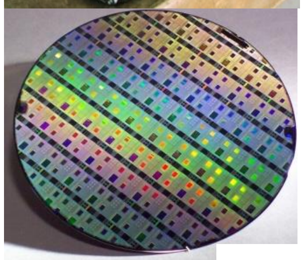
$$G_{las} = 5.6 \times 10^4 \frac{(h\nu - E_g)^{1/2}}{h\nu}$$

This prefactor depends on semiconductor material and can be modify by multiplying the ratio $$\left(\frac{m_r^*(Semiconductor)}{m_r^*(GaAs)}\right)^{3/2}$$ m_r^* is the reduced effective mass

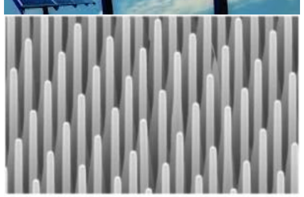
Laser structure

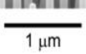
In LED photons emitted via spontaneous emission either leave the LED or are reabsorbed such that the photon density remains low and stimulated emission remains negligible. A key design feature of a laser is therefore to include **a set of mirrors** in a laser structure of **a chosen length** so that **photons of a chosen energy** will increase in density to achieve stimulated emission.

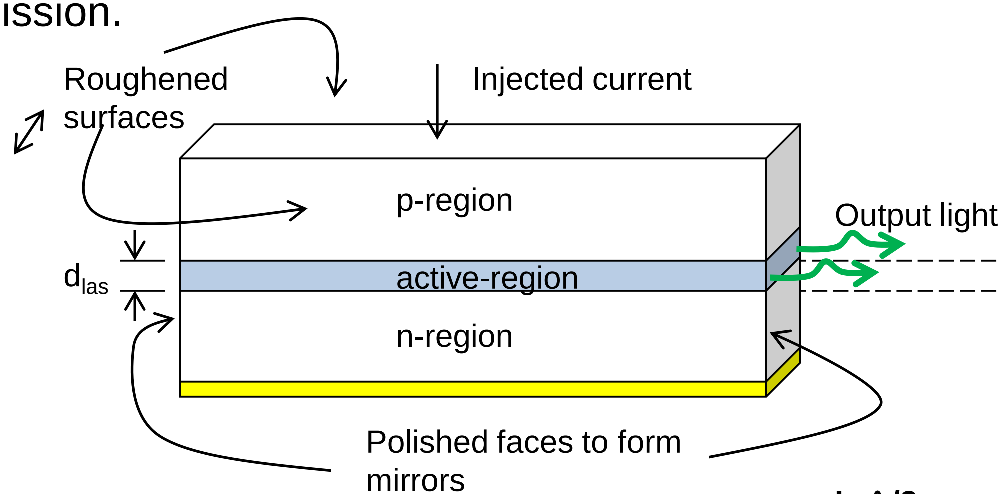


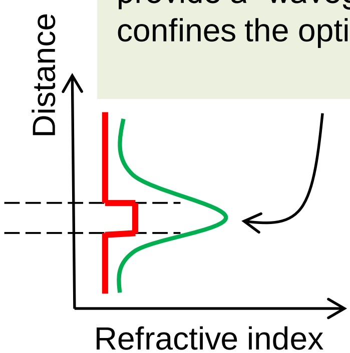


Laser bar width is usually 10-50 μm

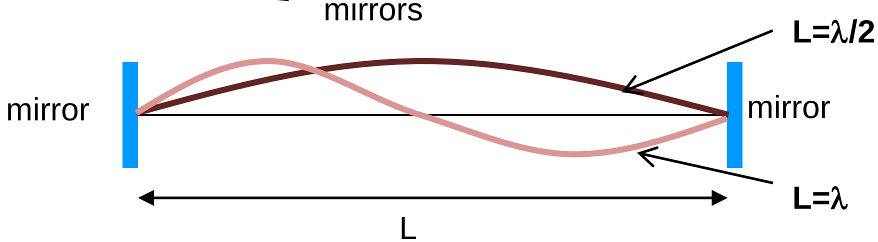








Use of higher dielectric constant in the active region provide a “waveguide” that confines the optical wave.

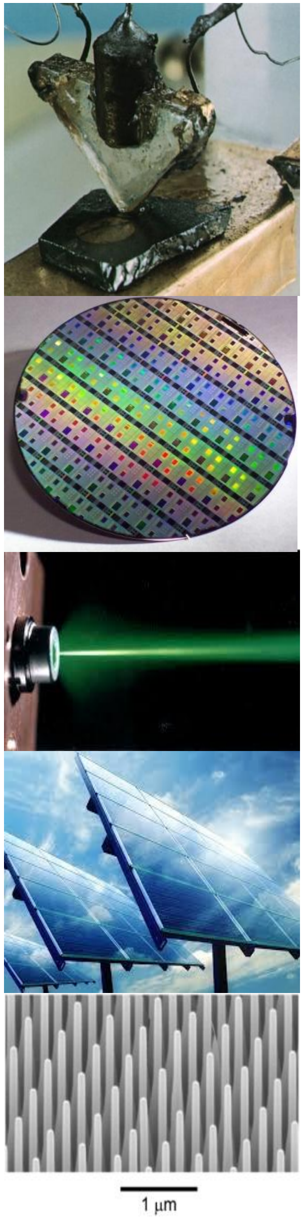


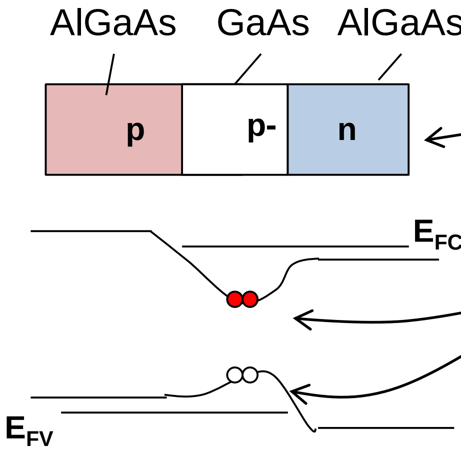
Resonant modes are produced for wavelengths satisfying the condition, $L=N\lambda/2$, where N is an integer and L is the cavity length.

Fabry-Perot Laser

http://www.youtube.com/watch?v=R_QOWbkc7UI

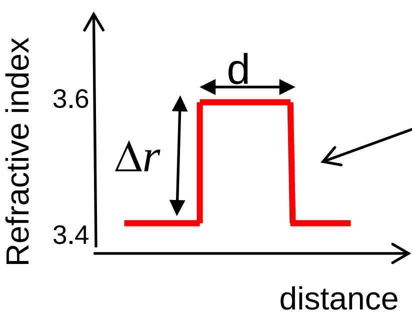
Double heterojunction



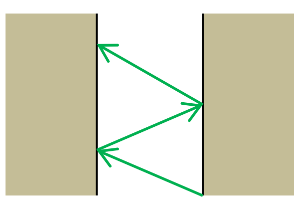


Wide bandgap AlGaAs does not absorb emitting photons, reducing cavity loss.

Carriers are confined to the active region to increase the radiative recombinaton.



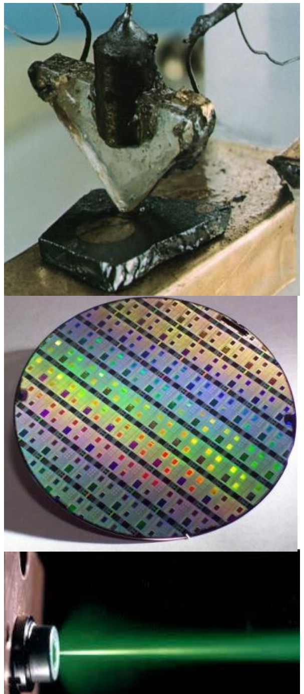
The refractive index change of 0.1-1% was achieved by increasing the doping concentration in the homojunction design. Using heterojunction the refractive index change of 5% can be achieved to improve the optical wave confinement significantly. Confinement factor of close to unity can be obtained (i.e internal reflection achieved to guide the wave in GaAs).



Guided wave

$$\Gamma \cong 1 - \exp(-\underbrace{C}_{\text{constant}}\underbrace{\Delta r}_{\text{change in refractive index}}\underbrace{d}_{\text{thickness of active region}})$$

Laser structure



The cavity gain is given by $G_{cavity} = g(h\nu)\Gamma$

Material gain that increases with injection current

Optical confinement factor of the active region. Γ~1 in double heterojunction laser.

The rate of arrival electrons (holes) into the active region is $\dfrac{JA}{q}$

Current density

Device area

The electron-hole pair recombination rate is $\dfrac{nAd_{las}}{\tau_r(J)}$

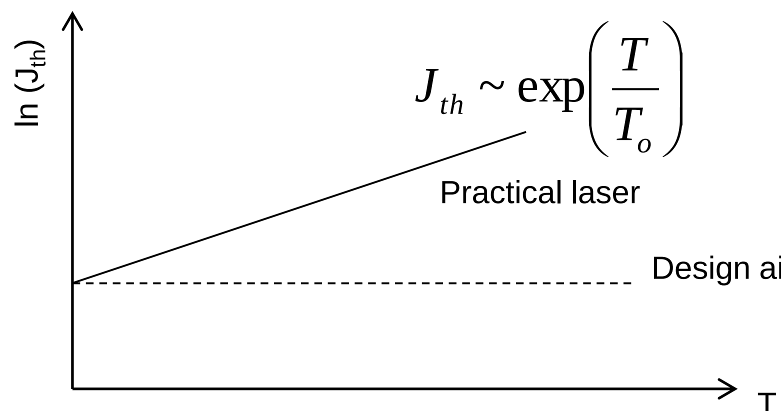
Radiative recombination time

Assuming a unity radiative efficiency we have and equating the two equations, at threshold above we have

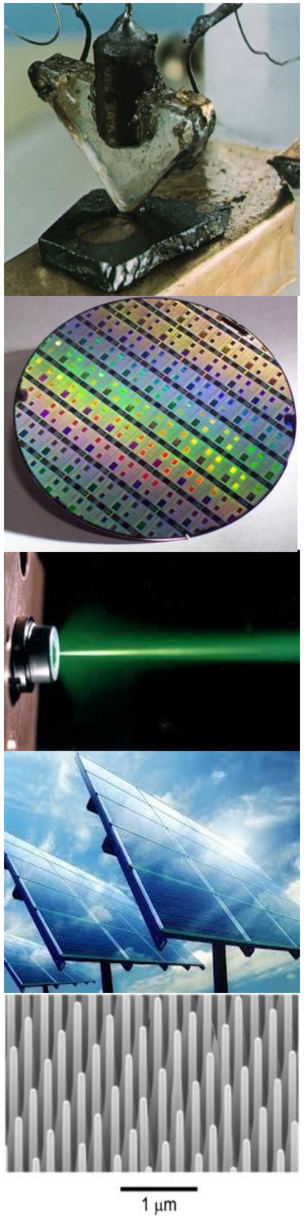
$$J_{th} = \frac{qd_{las}n_{th}}{\tau_r(J_{th})}$$

Increasing the active layer thickness, d_{las}, will also increase J_{th} and Γ in bulk laser. Therefore the bulk laser is not the most efficient structure as it will require a large J_{th} (~10^4 A/cm^2 in GaAs laser). Large current density is not desirable since it is important to minimise the power consumption and achieve high reliability with long lifetime. It is also well known that J_{th} is strongly dependent on temperature.

1 µm



Improved laser structures



We will focus on two aspects of laser structure that require improvement.

1) Light with different frequencies travel at different speeds, leading to pulse spreading in optical fiber communication. Therefore the stripe-geometry laser is not suitable for bit rate above 1 Gb/s. Laser structure improvement is needed to achieve a single frequency emission.

2) The threshold current should be made as low as possible and has a small temperature dependent as possible.

Distributed Feedback (DFB) laser

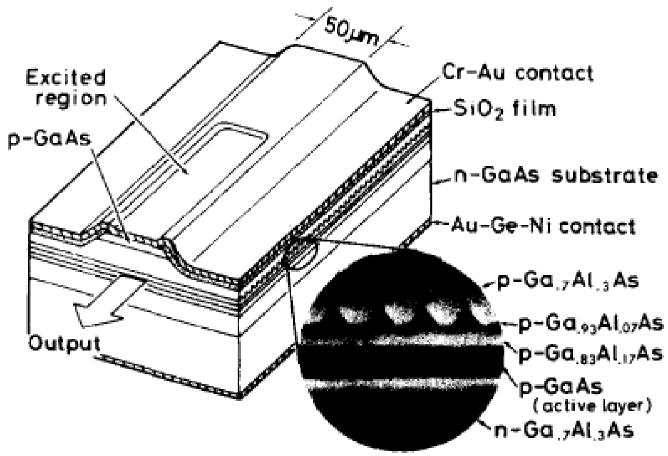


FIG. 1. Structure of the DFB laser with separate optical and carrier confinement.

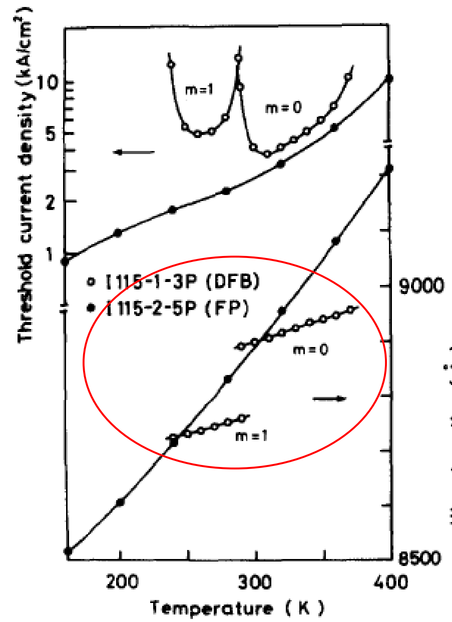


FIG. 2. Threshold current density and the lasing wavelength as a function of junction temperature. The period was 3814 Å in I115-1-3P. The results were obtained under pulsed operation.

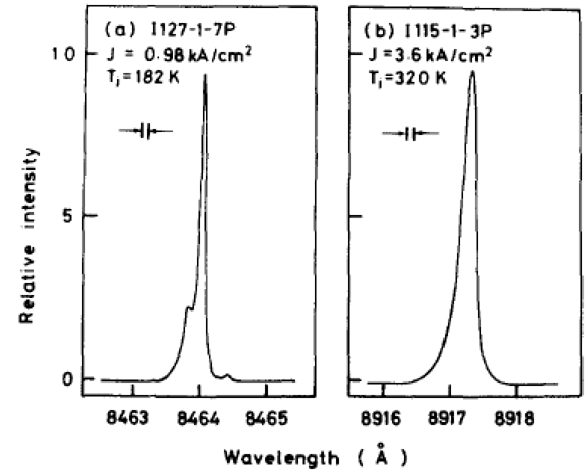


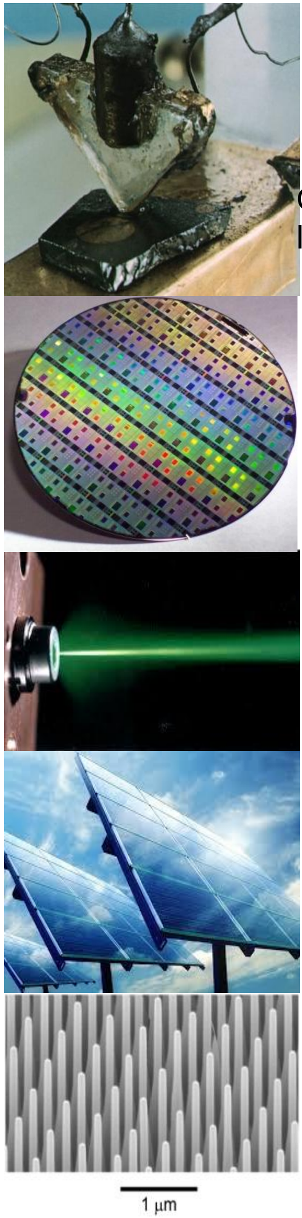
FIG. 3. Lasing spectra under cw operation. (a) Λ = 3648 Å, (b) Λ = 3814 Å.

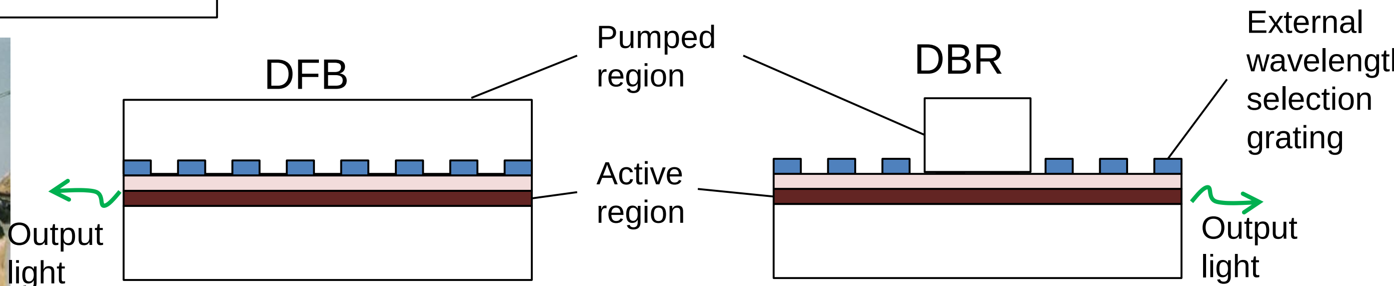
Applied Physics Letters, Vol. 27, No. 7, 1 October 1975

Single mode lasing

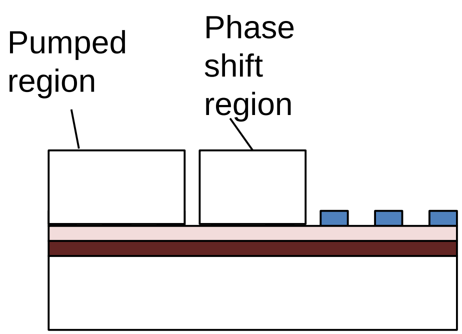
In a DFB structure, a periodic grating shown in fig. 1 is incorporated. The process involves etching of the grating, followed by regrowth of the top layers. The grating should be close to the active region to maximise interaction with the optical wave. However it should not be too close to the active region so that defects created during etching do not act as non-radiative recombination centers. The fabrication cost is therefore much more expensive than the simple Fabry Perot laser. However it offers a much narrower emission spectra of ~1Å compared to ~20Å in Fabry Perot laser. DFB is an important technology for optical communication.

Distributed Bragg Reflector (DBR) laser





The period of the grating is fabricated such that it will enhance the reflection at the chosen wavelength (and its higher harmonics). The emission wavelength is much less sensitive to temperature compared to FP. In FP the temperature dependence of bandgap determines the emission wavelength. On the other hand the wavelength selectivity in DFB and DBR is determined by the small temperature dependence of refractive index.



The semiconductor refractive index can be modified by the carrier density. By applying current or voltage to a “mode phase shift” section, the DBR laser can achieve much better single mode lasing. Note that in the DFB, the grating overlaps with the pumped.

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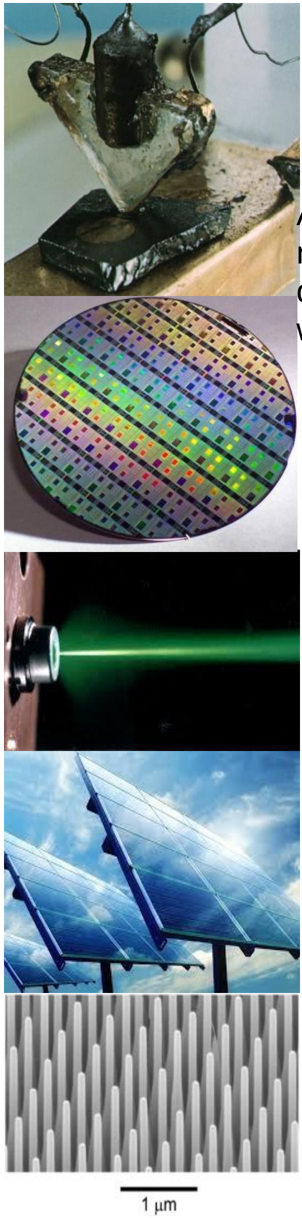
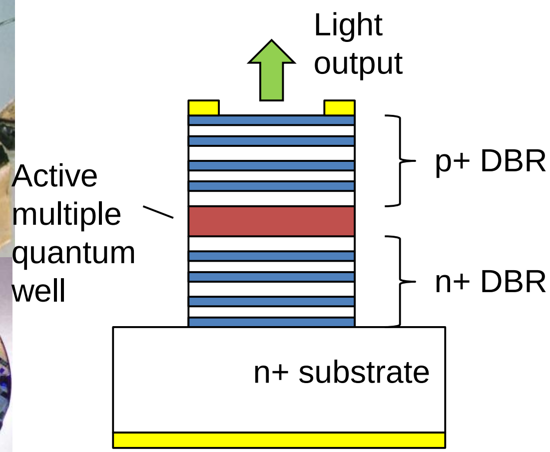
Vertical Cavity Surface Emitting Laser (VSCEL)





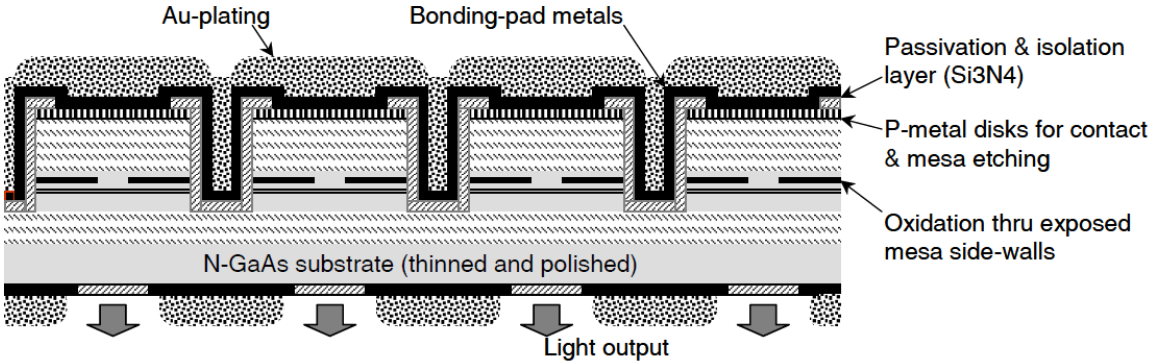
Light coupling from edge emitting laser is not the most efficient and it is costly. The VSCEL overcomes these by having light emitted vertically so that the optical fiber can be easily aligned. The p+ and n+ DBRs act as efficient mirrors (with >90% reflectivity) so that lasing is still possible within the very short vertical cavity compare to edge emitting laser. The high reflectivity, (compare to 30% in FP laser) dramatically reduce the cavity loss. Therefore the small cavity also provides an added benefit of low threshold current as well as for realization of laser 2-D array.

DBRs can be formed using two different semiconductors such as GaAs/AlAs or using semiconductor-dielectric combination such as Si/SiO. Key limitations of VSCEL include

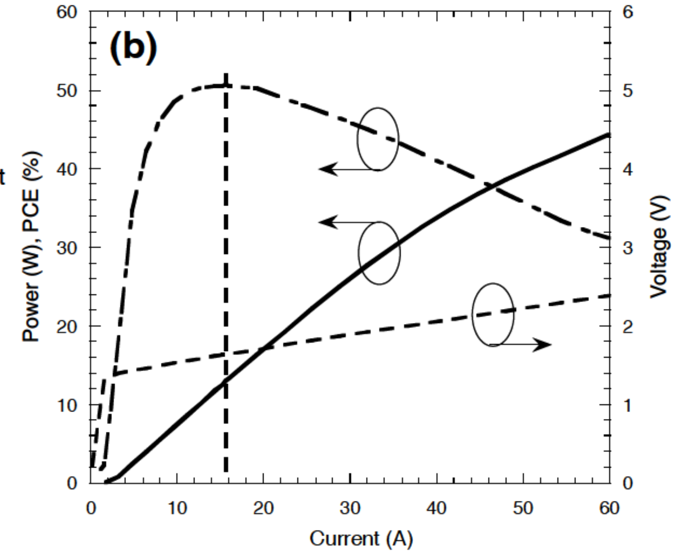
i) Charge injection is complicated by the thick DBR. In particular since the ring contact used (to allow light emission through the center), current injection is much higher at the edge compare to the center.

ii) Device heating will limit the device operation at high drive current. Loss of efficiency due to leakage current and Auger recombination occurs.

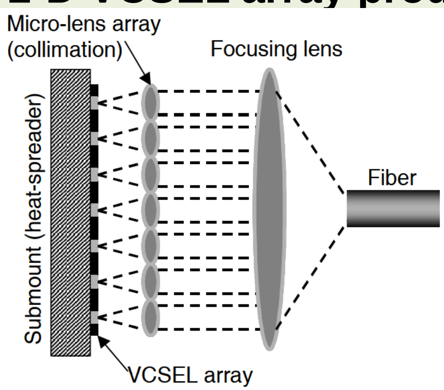
Vertical Cavity Surface Emitting Laser (VCSEL)

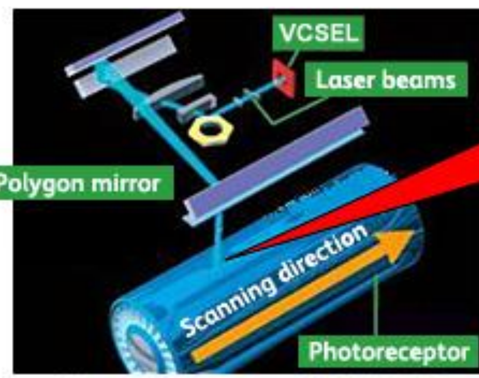


Proc. of SPIE Vol. 6908 690808-8

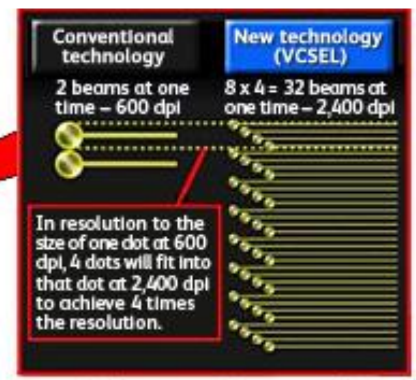


2-D VCSEL array produced 13W power output





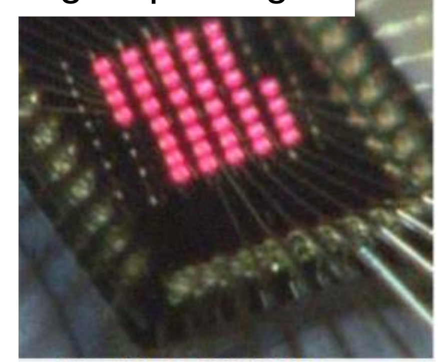
Schematic Diagram of VCSEL-ROS



Explanatory Diagram of True 2,400 dpi High Resolution (Comparison with conventional technology)

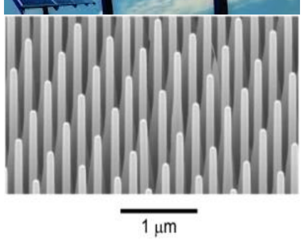
https://www.fujixerox.com/eng/company/technology/production/digital/vcsel_ros.html

Ricoh used a 40 channel VCSELs for digital printing

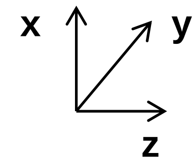


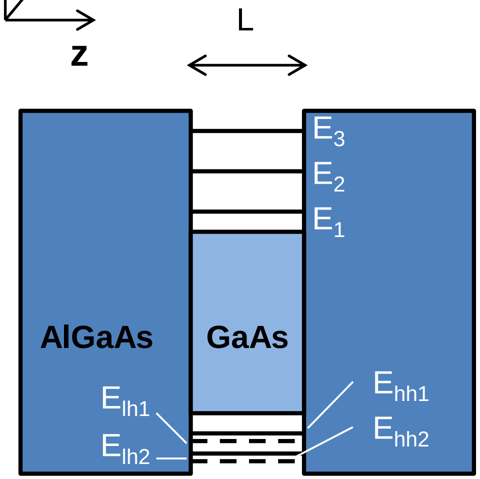
(b) 40ch VCSEL array

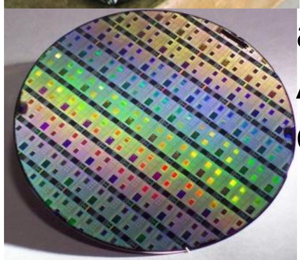
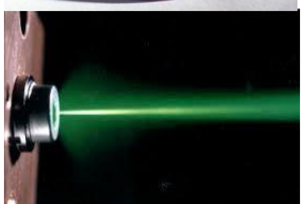
http://www.ricoh.com/about/company/technology/tech/038.html

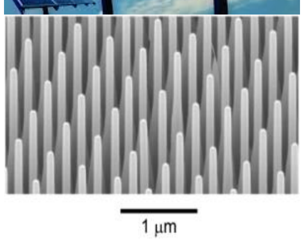


Quantum well lasers





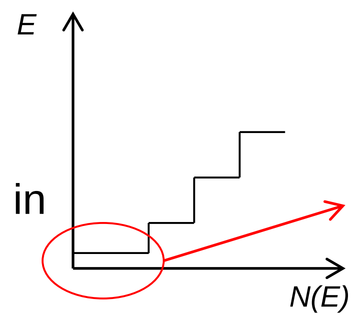


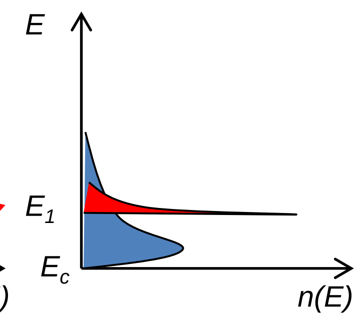
Why is quantum well useful in laser design?

Consider a GaAs/AlGaAs system. The quantum well is formed when the width of GaAs layer is reduced to 10-20 nm. This width is comparable to the de Broglie wavelength $\lambda_{Broglie}=h/p$ where h is the Planck constant and p is the carrier momentum.

Assuming an infinite barrier height, the quantised energy level is constant and is given by

$$E_n = \frac{1}{2m^*}\left(\frac{\pi\hbar n}{L}\right)^2$$





In each sub-band (E_1,E_2, E_3) the electron is in a 2-D world. Because of this the density of states also have a 2-D behaviour.

The parabolic form of conduction band density of states has been replaced by "staircase" form

	Bulk (3-D)	Quantum well (2-D)
Density of state	$N(E)=4\pi\left(\frac{2m^*}{h^2}\right)^{\frac{3}{2}}E^{\frac{1}{2}}$	$N(E)=\frac{4\pi m^*}{h^2}$
Total energy	$E(k)=\frac{\hbar^2k^2}{2m^*}$	$E_n(k_x,k_y)=\frac{1}{2m^*}\left(\frac{\pi\hbar n}{L}\right)^2+\frac{\hbar^2k_x^{\ 2}}{2m^*}+\frac{\hbar^2k_y^{\ 2}}{2m^*}$

* - $N(E)$ is derived in Appendix H in Semiconductor Devices Physics and Technology (Sze and Lee)

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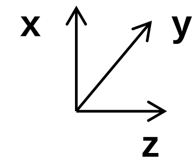
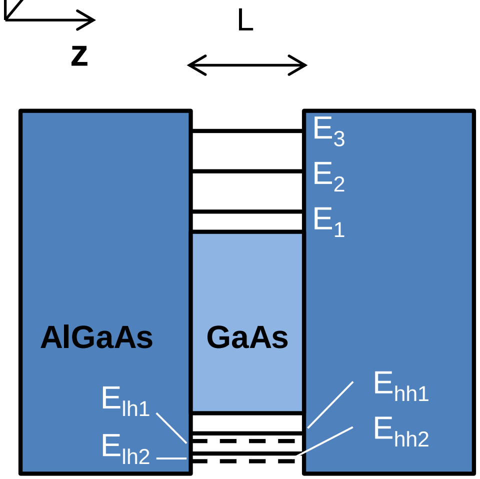
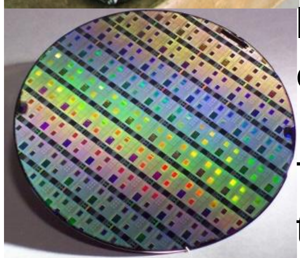
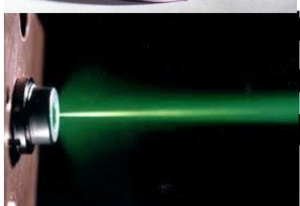
Quantum well lasers



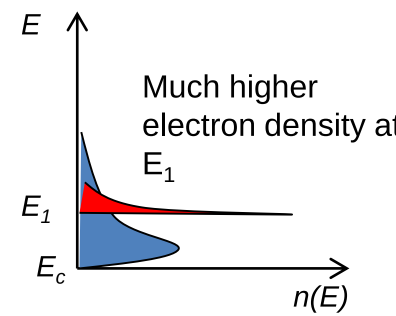




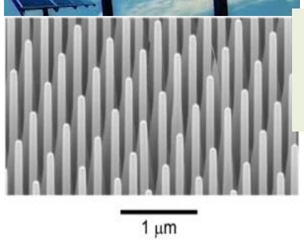
There is a group of electrons at E_1 and a group of holes at E_{hh1} available to initiate radiative recombination. Population in version is much easier to achieve in quantum well due to the higher density of states at E_1. Improvements offered by quantum well lasers over DH lasers include much **lower threshold current, high output power and high speed**.



Typical GaAs/AlGaAs quantum well lasers have threshold current density as low as 65A/cm^2, compare to 10^{4}A/cm^2 in bulk laser. The low current density means that sub-mA drive current is possible in quantum well lasers.



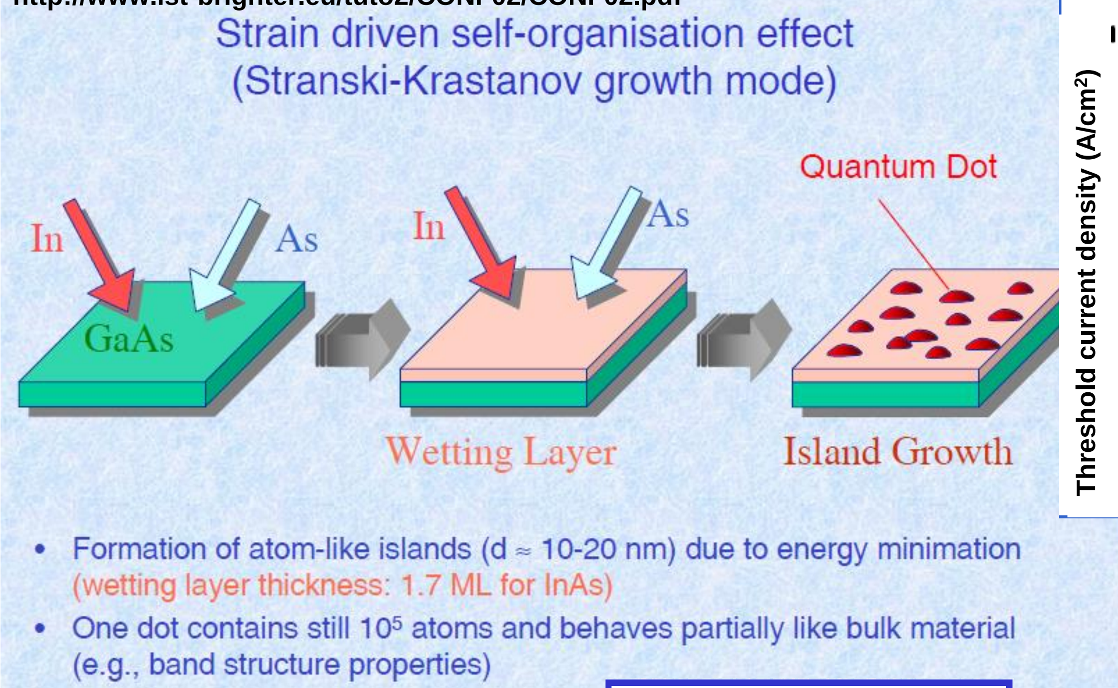
By using careful strained layer in the well, the density of states in the valence band can be further modified to achieve population inversion at even lower threshold current. The strain can be achieved by incorporating In to form InGaAs well.

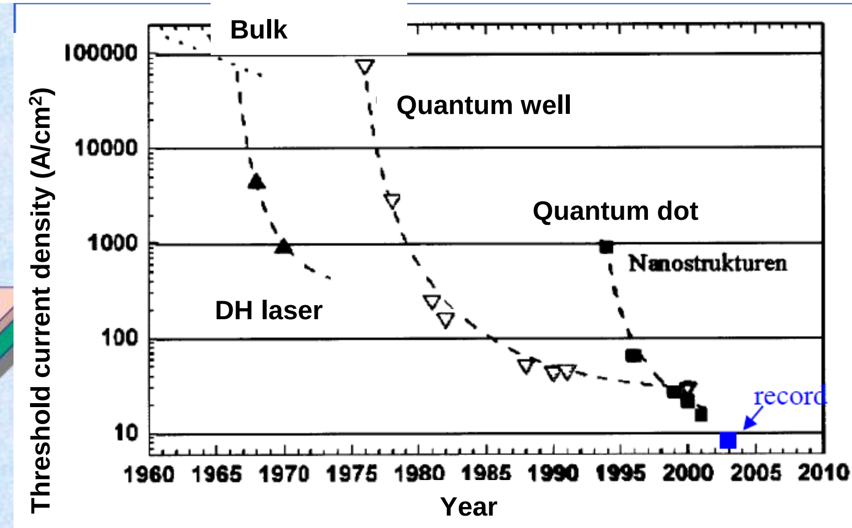


Quantum well laser is a key component of optical communication systems at 1300 and 1550 nm.

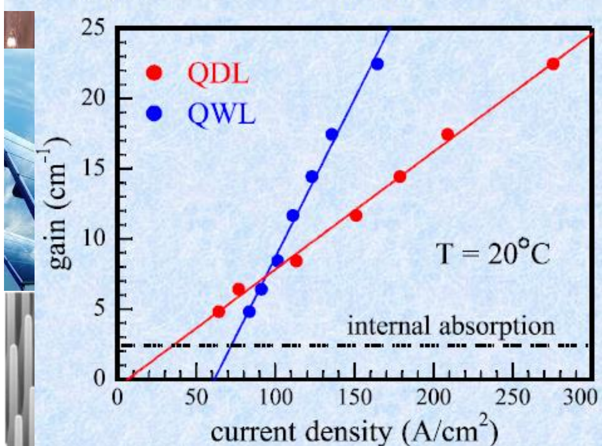
Quantum dot lasers

http://www.ist-brighter.eu/tuto2/CONF02/CONF02.pdf

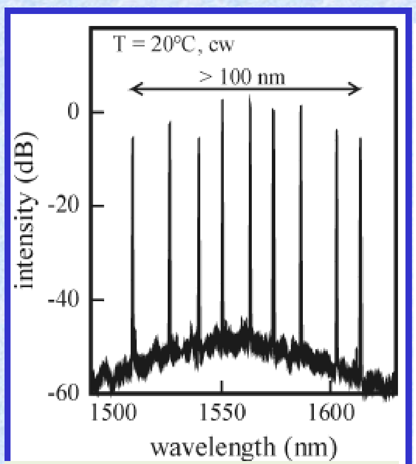




The electron is confined in all direction (i.e a 0D system). The density of states is defined by a delta-function. This leads to very low threshold current density and much better temperature stability too.

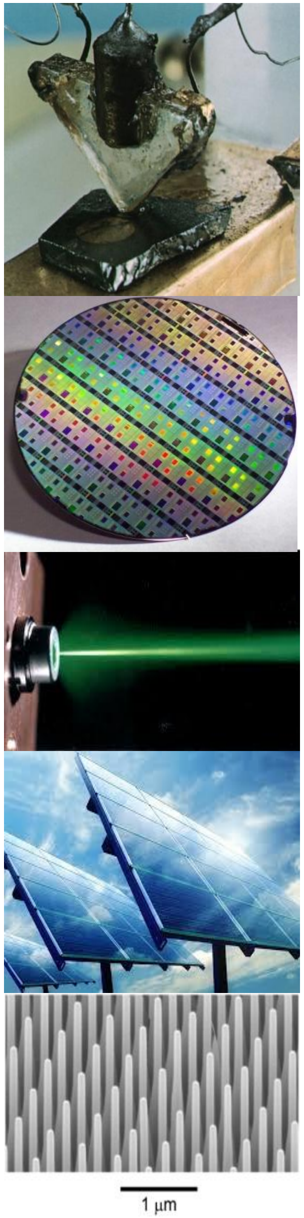


Lower threshold current

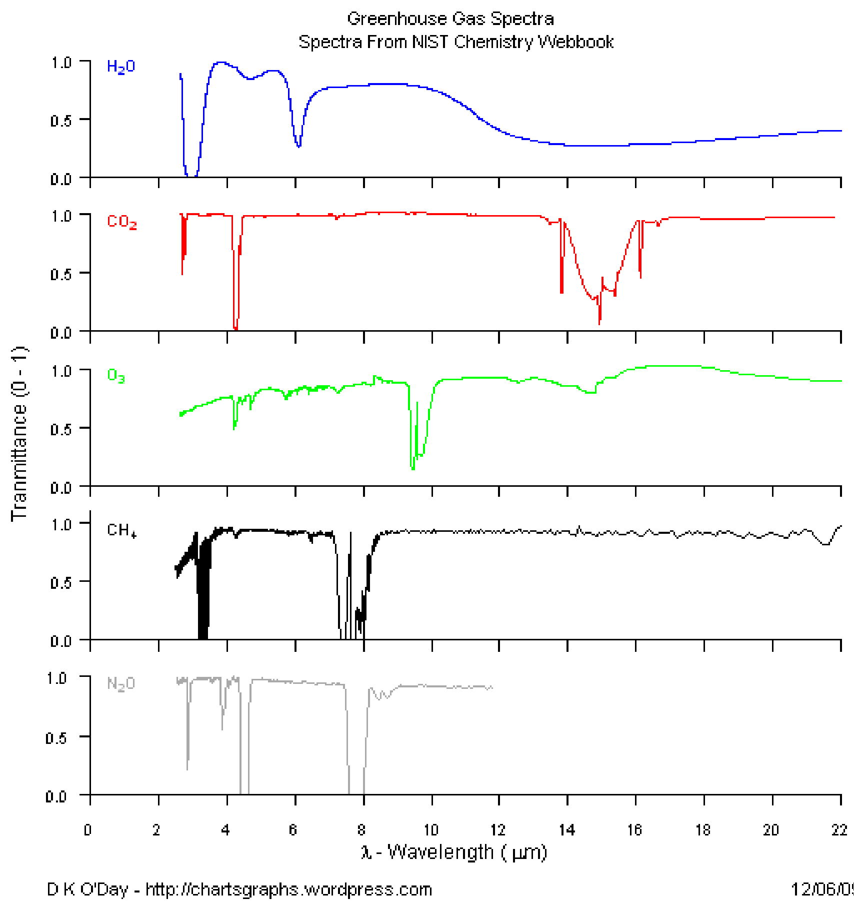


Wavelength tuning

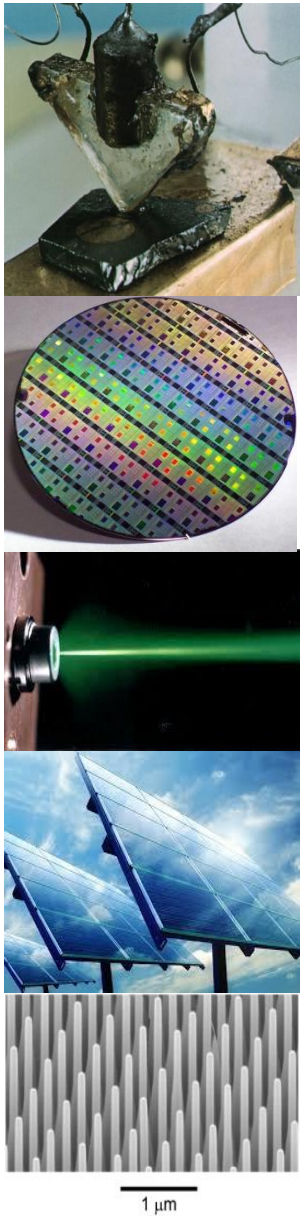
Infrared lasers



An important technology in analysis of gas and molecule due to the “infrared signature”.

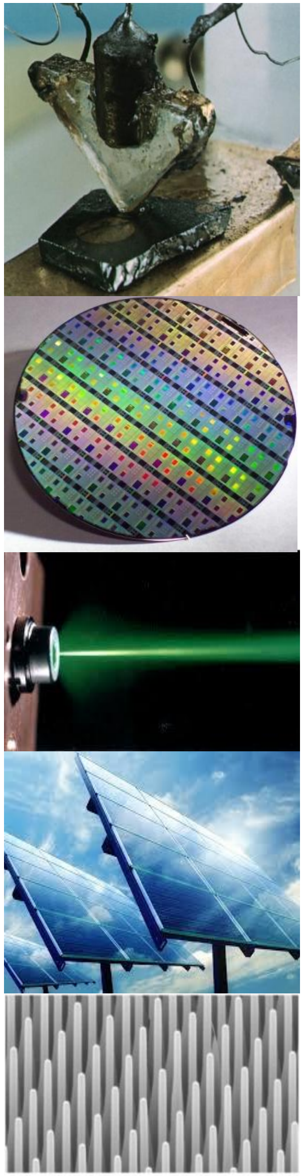


Infrared lasers



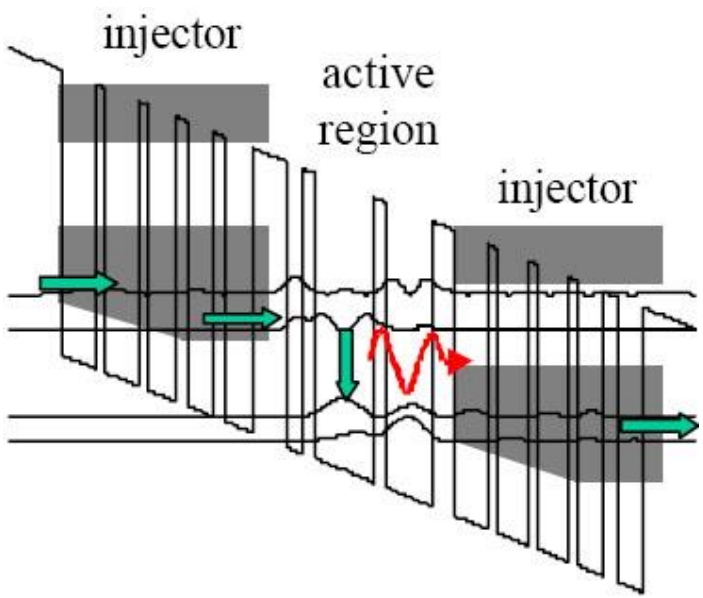
Bipolar lasers
-emission controlled by the bandgap
-emission in bulk material affected by thermal distribution leading to broader spectrum
-for infrared, Auger recombination is a limiting recombination rate. **) Auger recombination increases exponentially as the bandgap decreases. Hence it is a very dominant non-radiative recombination mechanism in narrow bandgap materials such as InSb, PbSe and HgCdTe. In addition there is no wide bandgap material that is lattice matched to InSb. Since Auger recombination reduces exponentially with temperature, cooling is usually required to achieve lasing in bulk materials. Therefore fabricating an efficient and low cost infrared laser is very challenging.**

Quantum cascade laser (QCL)



1 μm

The quantum cascade laser (QCL) is an important laser for the 3-5 μm, 8-12 μm and even in THz. The band diagram is shown below. The energy states are dependent on the layer thickness of the quantum well.
In the injector region, the quantum wells are designed such that under appropriate biasing condition, the energy states are aligned to allow electron to tunnel through the barriers. This enables the electron to move from a low energy state to a higher energy state.



The electron is subsequently injected into the active region containing quantum well with energy state separation that will produce the desired wavelength when the electron make the intra-band transition from the high to low energy states. After the photon emission the electron from the low energy state is transported to the injector region and the process is repeated. Typically the injector and active regions are repeated for 20-100 times to produce a QCL