EEE337 Semiconductor Electronics
EEE348 Electronics and Devices
(LEDs)

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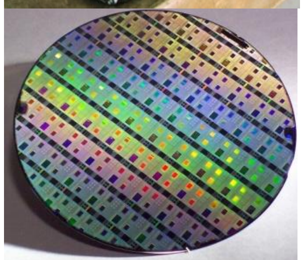
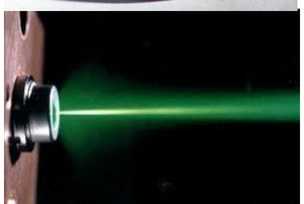
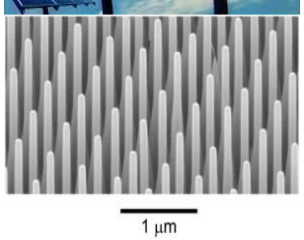
LED and Laser applications

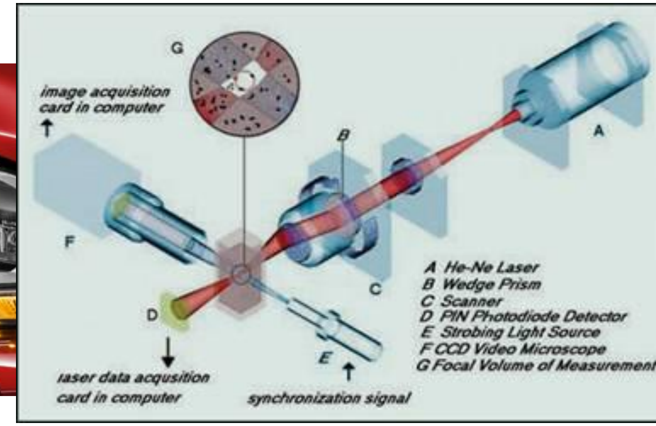




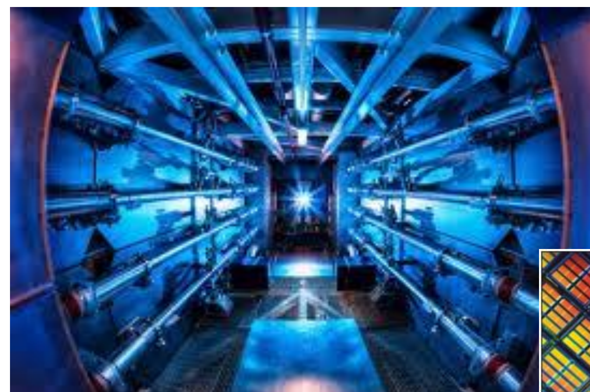


Lighting

Spectroscopy

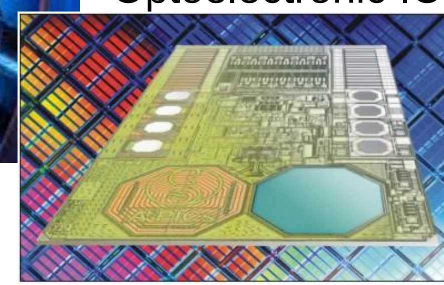


Optical communication



Nuclear fusion

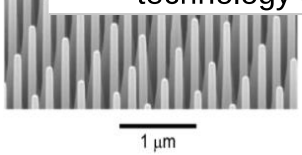
Optoelectronic IC



And many more!

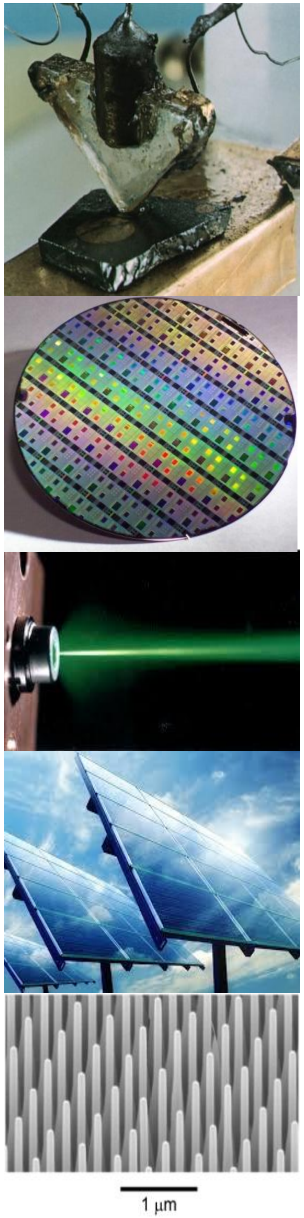
LED development

A short glance back over the history of the LED:	
1907	The Englishman Henry Joseph Round discovers that inorganic materials can light up when an electric current is applied. In the same year, he publishes his discovery in the journal "Electrical World". Since, however, he was working mainly on a new direction-finding system for marine transport, this discovery initially is forgotten.
1921	The Russian physicist Oleg Lossew again observes the "Round effect" of light emission. In the succeeding years, from 1927 to 1942, he examined and described this phenomenon in greater detail.
1935	The French physicist Georges Destriau discovers light emission in zinc sulfide. In honor of the Russian physicist, he calls the effect "Lossew light". Today Georges Destriau is credited as the inventor of electroluminescence.
1951	The development of a transistor marks a scientific step forward in semiconductor physics. It is now possible to explain light emission.
1962	The first red luminescence diode (type GaAsP), developed by American Nick Holonyak, enters the market. This first LED in the visible wavelength area marks the birth of the industrially-produced LED. **http://www.bbc.co.uk/news/technology-19886534**
1971	As a result of the development of new semiconductor materials, LEDs are produced in new colors: green, orange and yellow. The LED's performance and effectiveness continues to improve.
1993	Japanese Shuji Nakamura develops the first brilliant blue LED and a very efficient LED in the green spectrum range (InGaN diode). Some time later he also designs a white LED..
1995	The first LED with white light from luminescence conversion is presented and is launched on the market two years later.
2006	The first light-emitting diodes with 100 lumens per watt are produced. This efficiency can be outmatched only by gas discharge lamps.
2010	LEDs of a certain color with a gigantic luminous efficacy of 250 lumens per watt are already being developed under laboratory conditions. Progress continues to surge ahead. Today, further development towards OLED is seen as the technology of the future.



http://www.osram.com/osram_com/news-and-knowledge/led-home/professional-knowledge/led-basics/led-history/index.jsp

LED vs. incandescent



LED lamps instead of incandescent lamps – great savings potential!			
	OSRAM LED STAR CLASSIC A 40	**Conventional incandescent lamp**	**Comparison**
Lifespan	up to 15 years (15,000 hours)	1 year (1,000 hours)	15 times longer lifespan
Power consumption (with identical light intensity)	8 watt	40 watt	32 watt energy savings
Annual savings potential (at 2.7 hrs. daily operating time)		with use of an LED lamp	**= 8,13 euros**
		with use of 10 LED lamps	**= 81,30 euros**

Electricity costs assumed: 0,25 €/kWh

http://www.osram.com/osram_com/news-and-knowledge/led-home/led-trends/led-lamp-for-less-than-10-euros-led-star-classic-a/index.jsp

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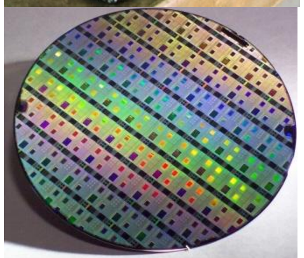
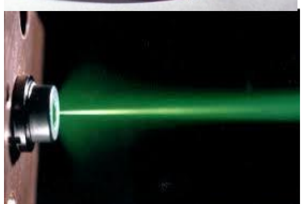
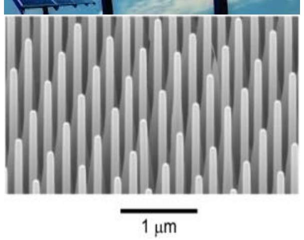
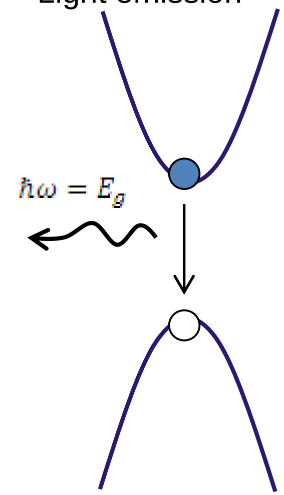
Light emission







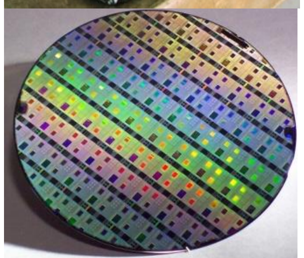
When an electron from the conduction band recombines with a hole in the valence band, a photon with energy very close to the bandgap E_g is emitted in a radiative recombination. Since conservation of energy and momentum is necessary the direct bandgap material has a much higher radiative recombination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

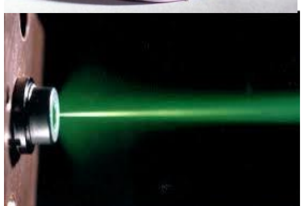


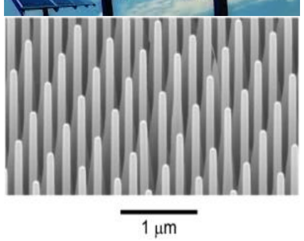
The simplest structure to achieve light emission is a forward biased homojunction pn junction. Not surprisingly this refers to the light emitting diode (LED), which is very attractive for display and low speed optical communication. The emission wavelength of LED is relatively broad and its modulation speed is limited.

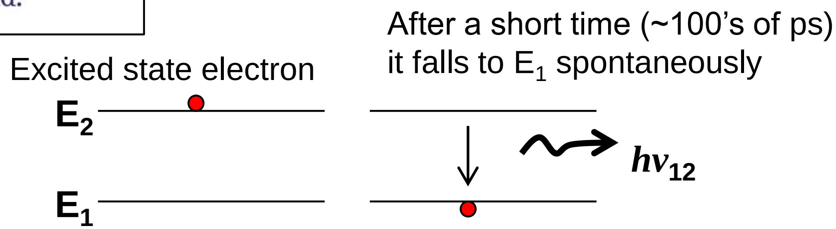
To achieve radiative recombination high concentrations of electrons and holes are required. By forward biasing the LED high concentrations of electrons and holes can be injected into the active region.

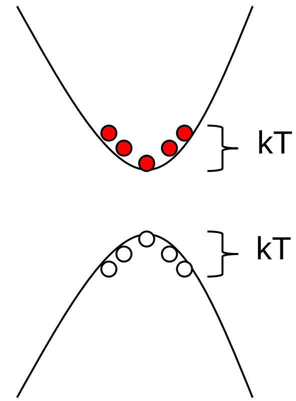
LED structure











$$\hbar\Delta\omega \approx kT$$

$$\Delta\lambda \approx \frac{kT\lambda^2}{hc}$$

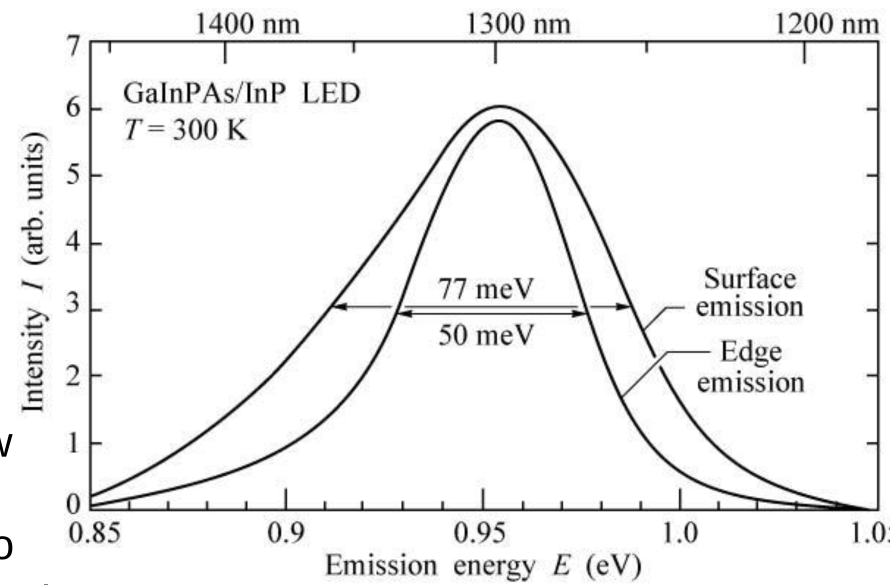
The spontaneous emission limits the modulation speed of LED. The recombination time is

$$\tau_o = \frac{0.88}{\hbar\omega(eV)} \quad ns$$

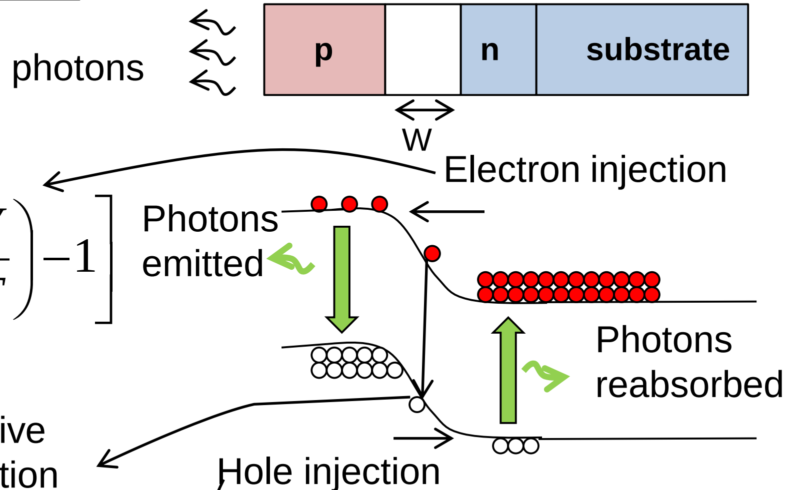
For instance if the spontaneous emission time is 500 ps,

$$\Delta f = \frac{1}{2\pi \times 500 \times 10^{-12}} = 318\,MHz$$

Hence LED is not suitable for high speed communication (above a few GHz). In addition the emission wavelength is typically broad due to the carrier distribution (due to thermal energy distribution) in the band structure.



LED structure



$$J_e = \frac{qD_e n_p}{L_e}\left[\exp\left(\frac{qV}{kT}\right)-1\right]$$

$$J_{GR} = \frac{qn_i W}{2\tau}\left[\exp\left(\frac{qV}{2kT}\right)-1\right]$$

$$J_h = \frac{qD_h p_n}{L_h}\left[\exp\left(\frac{qV}{kT}\right)-1\right]$$

The simplest LED structure is a forward biased homojunction pn diode.

The injection efficiency is given by

$$\gamma_{inj} = \frac{J_e}{J_e + J_{GR} + J_h}$$

To maximise light emission, the radiative recombination should occur close to the surface since photons emitted deep in the structure can be reabsorbed. To achieve this J_e should be the dominant current component.

How can we reduce J_{GR} and J_h?

We can increase the doping in the n-region such that the minority hole concentration is low, i.e when $n_p >> p_n$, $J_e >> J_h$.

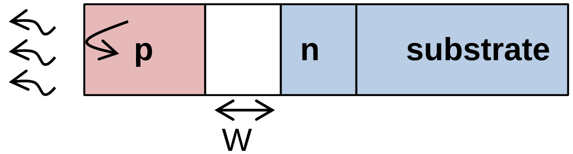
We need to minimise defects in the diode to make $J_{GR} \rightarrow 0$.

If $J_e >> J_h$ and $J_{GR} \rightarrow 0$, $\gamma_{inj} \rightarrow 1$.

1 µm

LED structure

photons



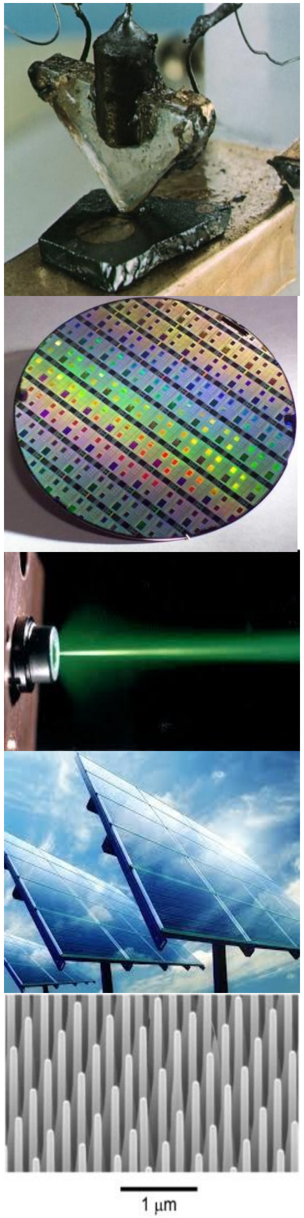
Photons emitted

Unfortunately not all the photons emitted can escape the LED structure due to internal reflection at the semiconductor-air interface. The refection coefficient is

$$R_{reflect} = \left(\frac{n_{semiconductor} - n_{air}}{n_{semiconductor} + n_{air}} \right)^2$$

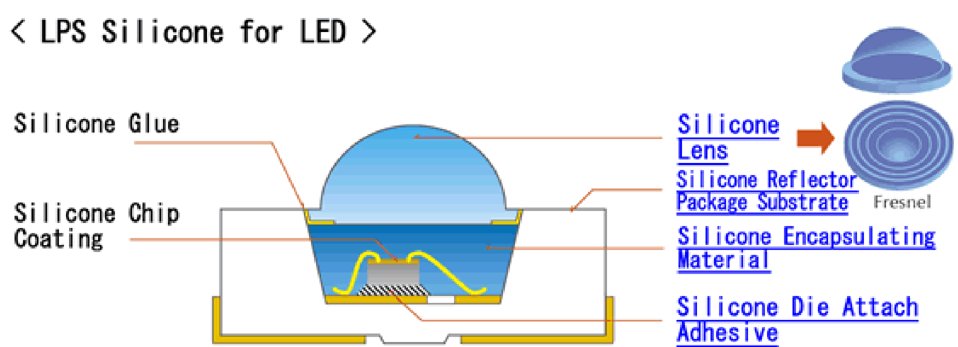
The refractive index in semiconductor is high. For instance in GaAs n_{GaAs} = 3.66 and hence only 67% of photons are transmitted. To minimise this usually a layer of dielectric or encapsulated dielectric dome is used. The dielectric refractive index (~1.5) is usually chosen to reduce reflection loss. In addition there is also loss due to internal reflection. The critical angle is given by

$$\theta_c = \sin^{-1}\left(\frac{n_{air}}{n_{semiconductor}} \right)$$



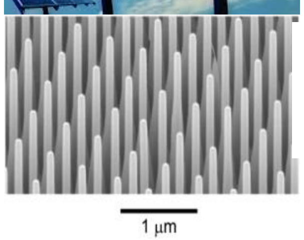
The three loss mechanisms discussed are

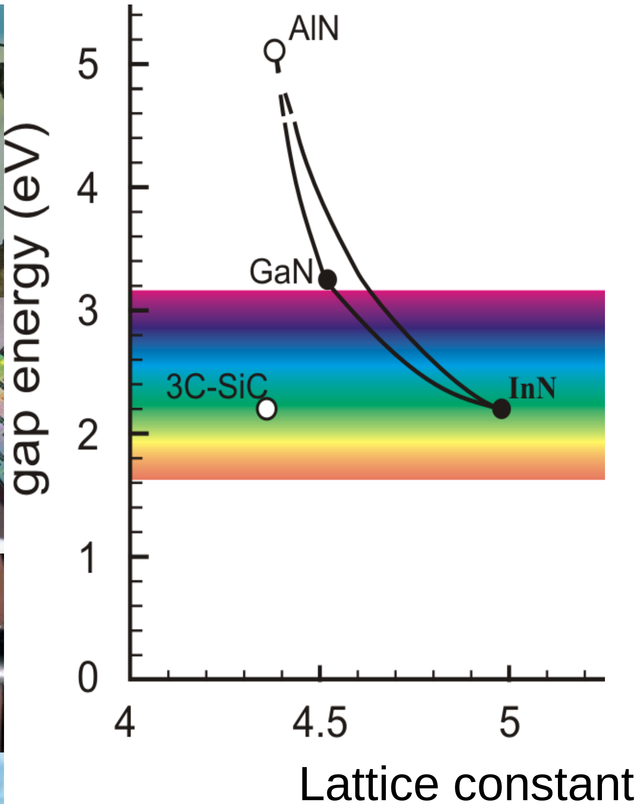
Re-absorption of photons
Transmission loss
Internal reflection



http://www.shinetsu-encap-mat.jp/e/product/k_l/lds/

Materials for LEDs

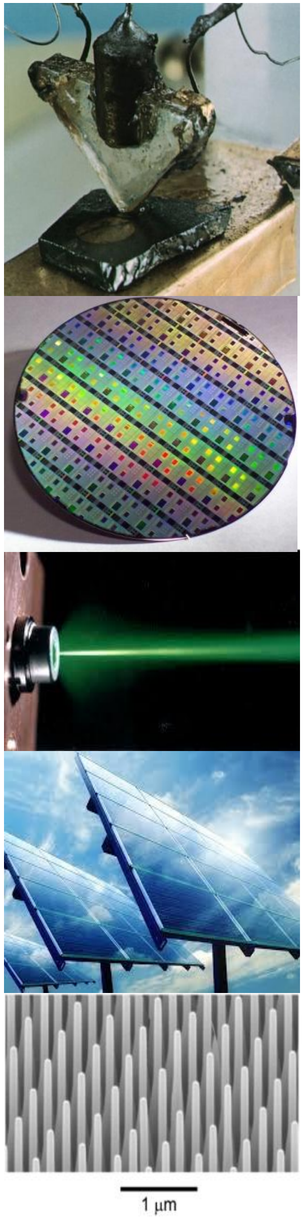




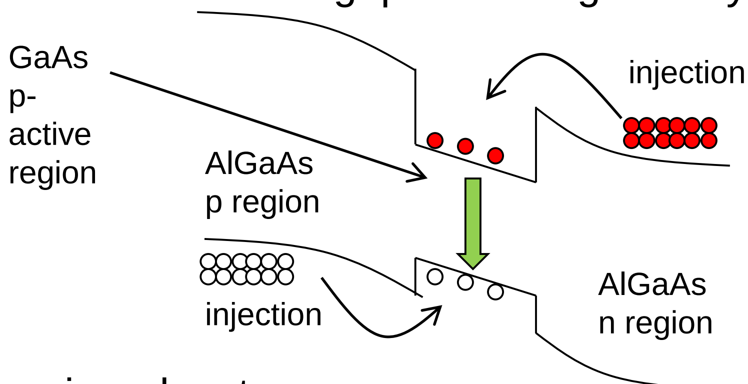
Semiconductor	Bandgap (eV)	Wavelength
$GaAs_{1-y}P_y$ (direct band gap)	1.42-1.98 (y=0-0.45)	626 to 873 nm (red to near IR) $GaAs_{0.6}P_{0.4}$:660 nm
$GaAs_{1-y}P_y(N)$ (indirect band gap)	1.98-2.26 (y>0.45)	Doped with N to create a fixed energy recombination centre. 550 nm to 620 (yellow-green to red). GaP(N):550-570 nm $GaAs_{0.4}P_{0.6}$: 620 nm $GaAs_{0.15}P_{0.85}$: 590 nm
$Ga_xIn_{1-x}As_{1-y}P_y$		1100-1600 nm $Ga_{0.47}In_{0.53}As$: 1550 nm $Ga_{0.27}In_{0.73}As_{0.63}P_{0.37}$: 1300 nm
$Ga_xIn_{1-x}N$	Depending on MQW design	340, 430,590 nm

InGaN and AlGaN are not lattice matched to GaN. Hence the need to use MQW since growth of bulk will lead to excessive defects.

Advanced LED structures



A major limitation of the homojunction LED is that the emission has to occur close to the surface. As we know the density of defect states is high near the surface. This leads to increased non-radiative recombination. In addition since the electrons injected from n-region can diffuse a long distance before recombining with holes, light can be emitted from a large volume. Fortunately as we have lattice matched wide bandgap materials, we can adopt a **double heterostructure** to confine the electrons and holes such that the recombination occurs in the narrow bandgap active region only.



The two main advantages are
i) Since electron cannot enter the wide bandgap p layer, they do not suffer surface recombination.
ii) The photons emitted is also not absorbed in the wide bandgap p and n layers.

GaAs/AlGaAs on GaAs and InGaAs/InGaAsP, InGaAsP/InP on InP are important combinations of double heterostructure LED.

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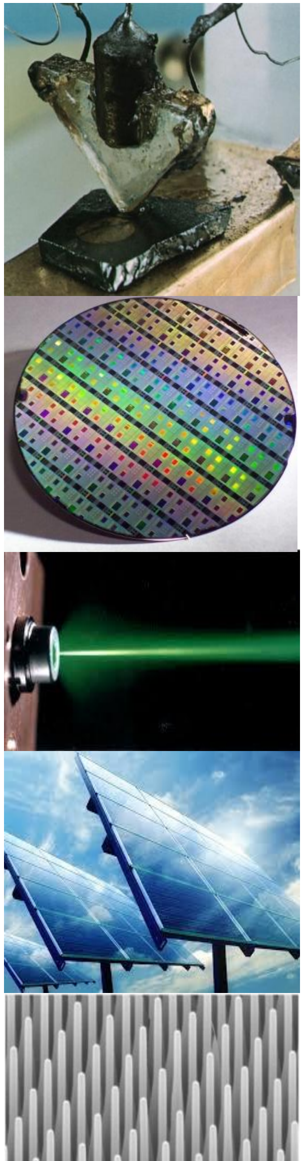
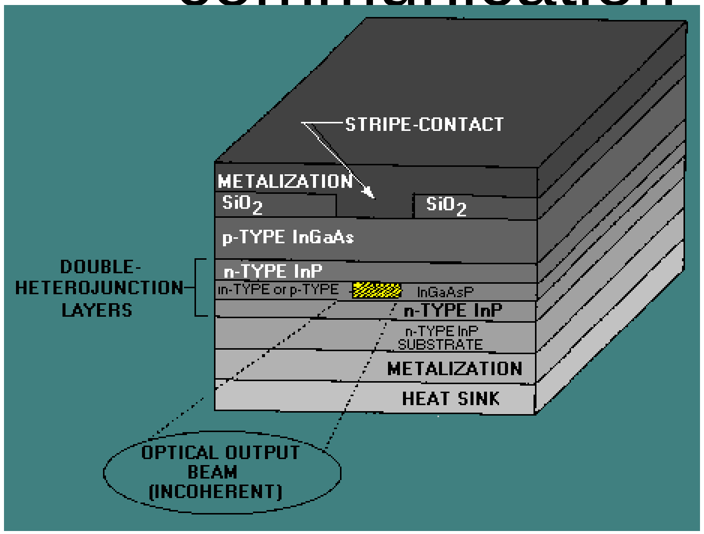
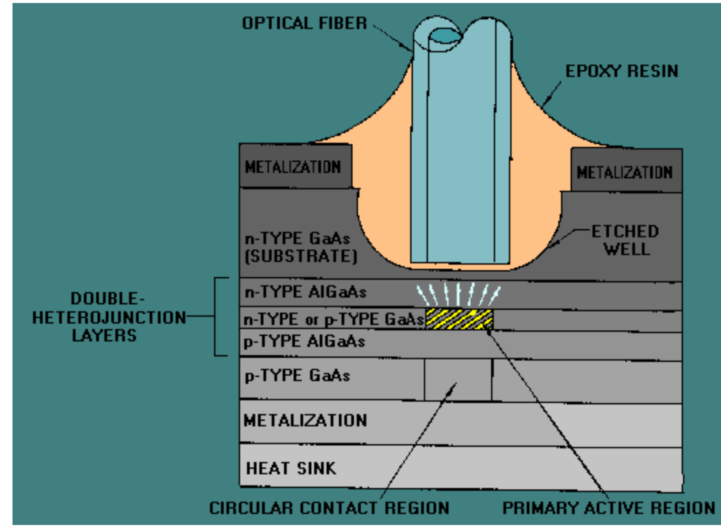
Advanced LED structures for data communication



1 µm



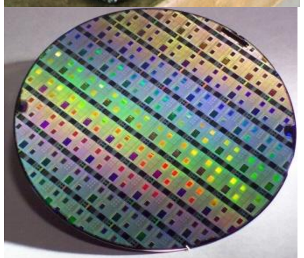
Wide bandgap cladding layers confine electrons and holes in the active region as well as guide the light so that light is emitted laterally. The edge emitting LEDs can be used up to typically 400 Mb/s with either single mode and multimode fibers. The front facet is coated with antireflection dielectric while the rear facet polished to reflect light so that light is emitted through the front facet only.

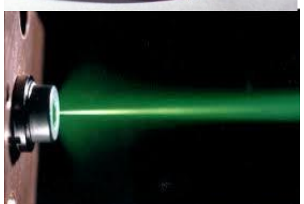


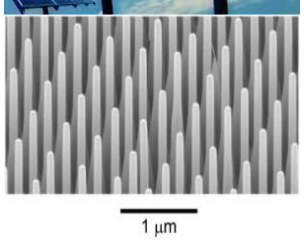
http://www.tpub.com/neets/tm/110-4.htm

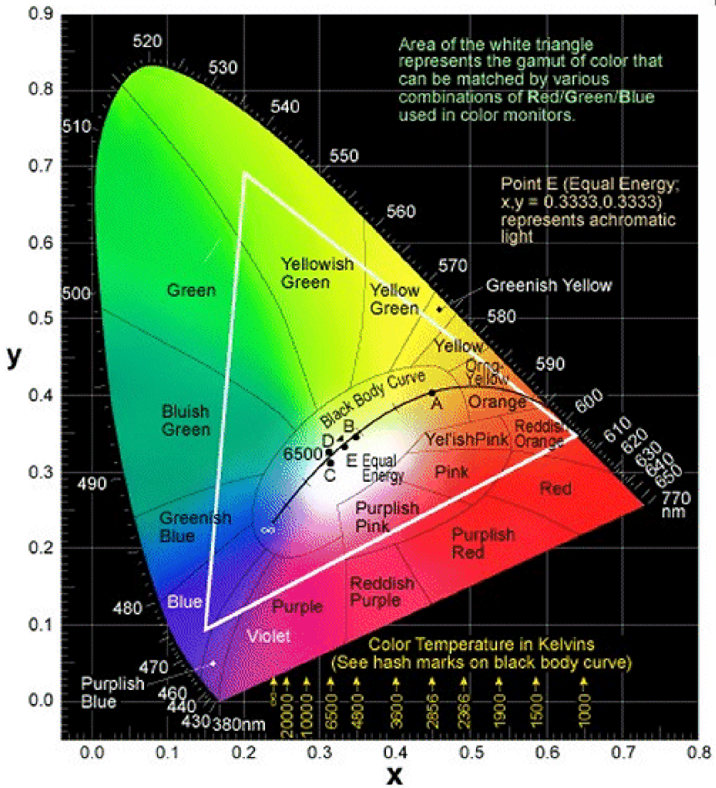
A well is etched into the substrate to allow direct fiber coupling. Surface emitting LEDs (SLEDs) are typically used in low bit rate data transmission, up to 250 Mb/s. They are mostly used with multimode fibers.

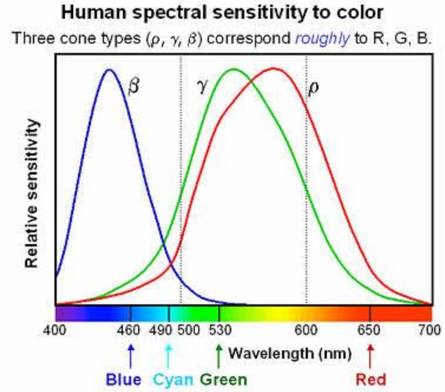
LEDs for lighting and display











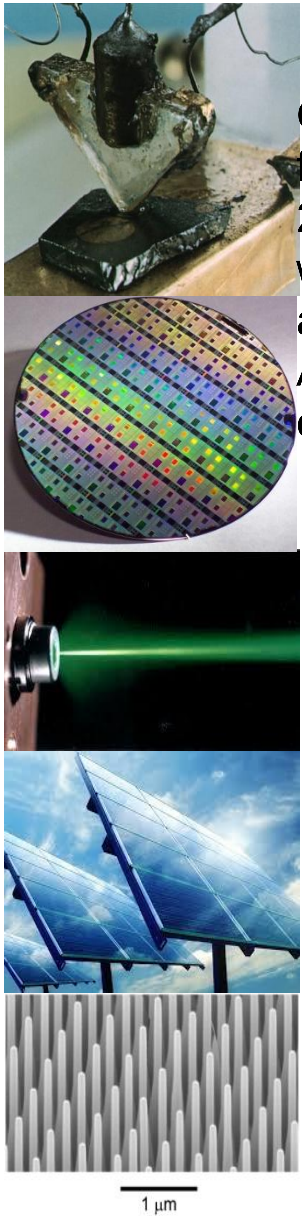
https://www.youtube.com/watch?v=Psbt2JvjWg0&feature=c4-overview-vl&list=PLS0CO0PT_kEJ7V1WlDeHdpXpgjQsq7zJI

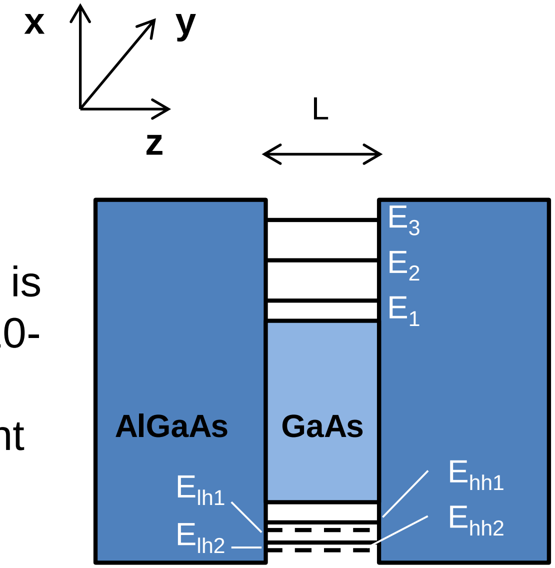
http://www.animations.physics.unsw.edu.au/light/eye-colour-vision/index.html

Specific combinations of RGB can produced a desired colour. By mixing two or more colours “white” can be produced. For example 450 & 525 & 626 nm (tips of the white triangle). All colour within the triangle can be produced by mixing these wavelengths.

The LED structure discussed so far are not fully optimised to achieve the highest efficiency required for energy efficient lighting and display.

Quantum well LEDs

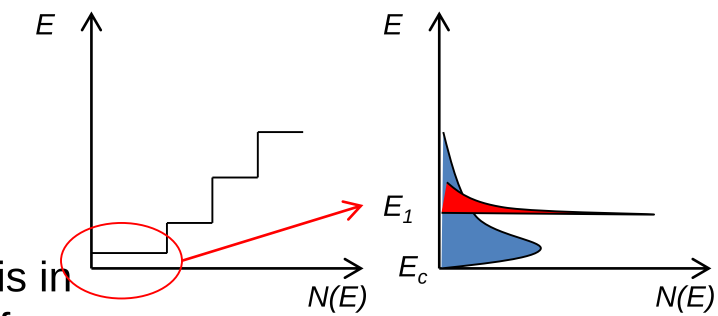




Why is quantum well useful in LED design?

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

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

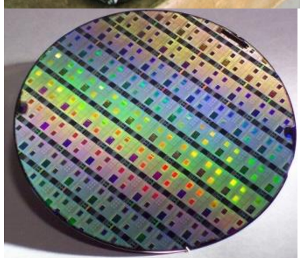
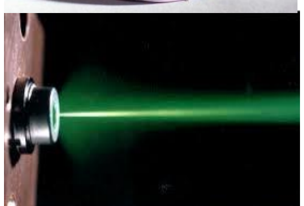


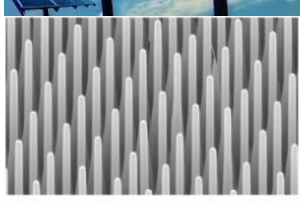
In each sub-band (E_1,E_2, E_3) the electron is in a 2-D world. Because of this the density of states also have a 2-D behaviour.

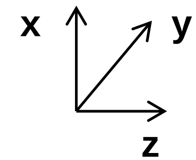
The parabolic form of conduction band density of states has been replaced by "staircase" form

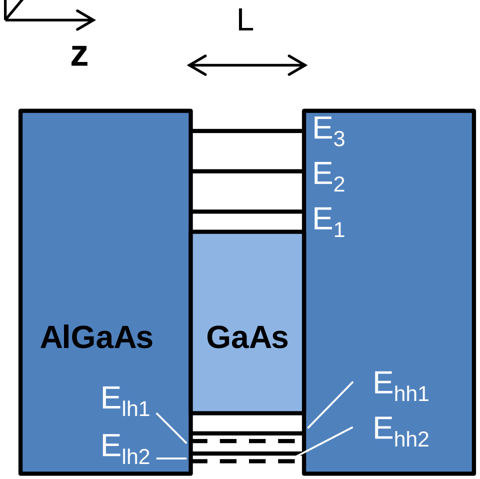
$$N(E)dE = \frac{4\pi m^*}{h^2}\sum_i H(E-E_i)dE$$

Quantum well LED

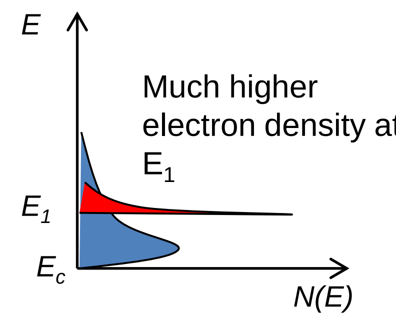










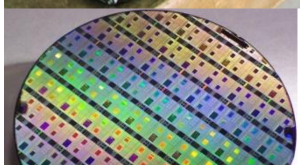
There is a group of electrons at E_1 and a group of holes at E_{hh1} available to initiate radiative recombination. Population in version is much easier to achieve in quantum well due to the higher density of states at E_1. Improvements offered by quantum well LEDs over DH LEDs include much **lower threshold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

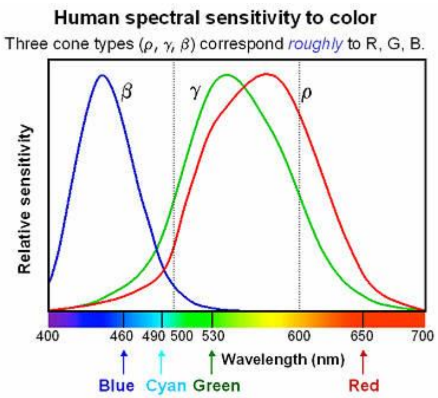


	Bulk (3-D)	Quantum well (2-D)
Density of state	$N(E) = 4\pi\left(\frac{2m^*}{h^2}\right)^{\frac{3}{2}} E^{\frac{1}{2}}$	$N(E) = \frac{4\pi m^*}{h^2}$
Total energy	$E(k) = \frac{\hbar^2 k^2}{2m^*}$	$E_n(k_x, k_y) = \frac{1}{2m^*}\left(\frac{\pi\hbar n}{L}\right)^2 + \frac{\hbar^2 k_x{}^2}{2m^*} + \frac{\hbar^2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

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

Near IR LED

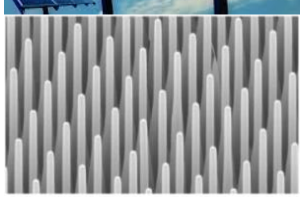




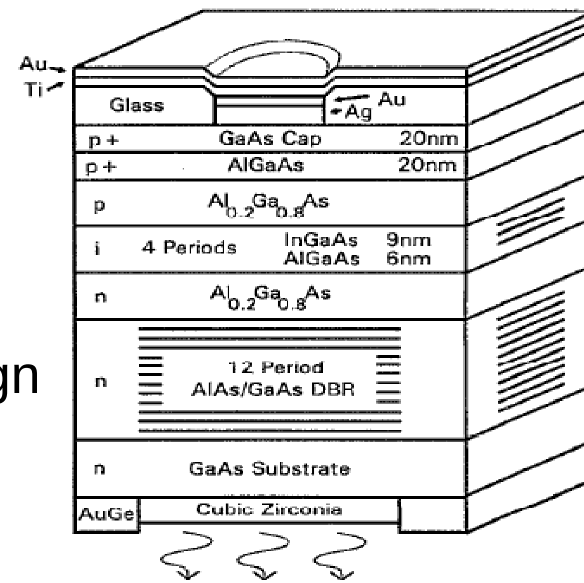
Applications such as remote control, infrared communication and Light Detection and Ranging (LIDAR), it is important to operate outside the human eye absorption bands.
-Wavelengths around 850 nm will still have emission around 700 nm.
-Wavelength above 900 nm with narrow emission spectral is required.

Table 1. Markets of high power infrared LEDs

- Surveillance cameras, outdoor floodlights·
- Light sources for automotive cameras
- Night vision system
- Light sources for license plate readers
- FA, and various sensors for domestic uses
- Range finding sensors for digital cameras
- Infrared data communications


1 µm

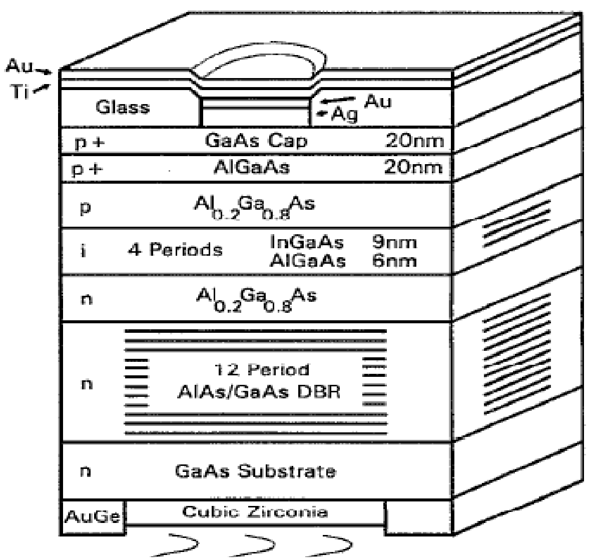
-InGaAs with bandgap of 1.319 eV is required.
-Employs a multiple quantum well design so that InGaAs can be grown on lattice mismatched GaAs substrate.

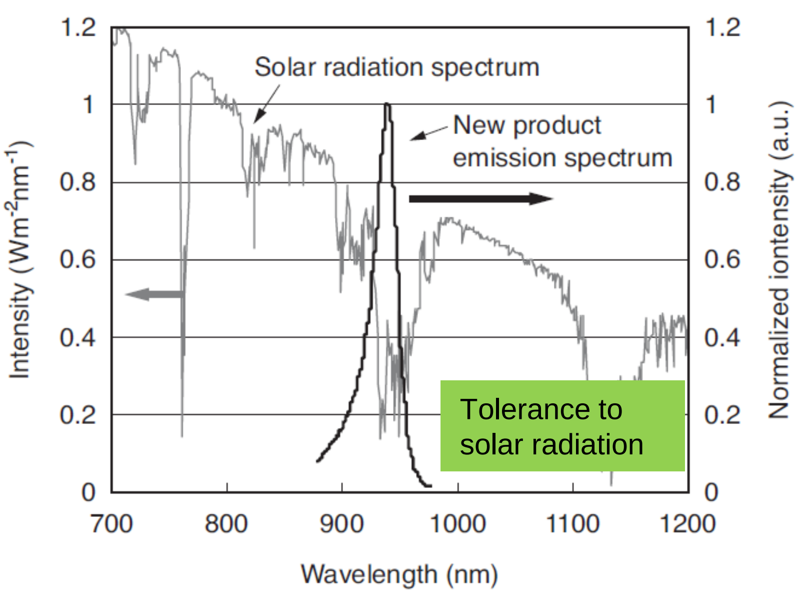


Appl. Phys. Lett. 63 (19), 8 November 1993

Near IR LED

-Active region consists of $In_{0.16}Ga_{0.84}As/Al_{0.2}Ga_{0.8}As$ Quantum Well.
-Transparent wide bandgap AlGaAs p and n layers
-Ag back reflecting mirror, AlAs/GaAs forms another mirror to form a resonant cavity LED





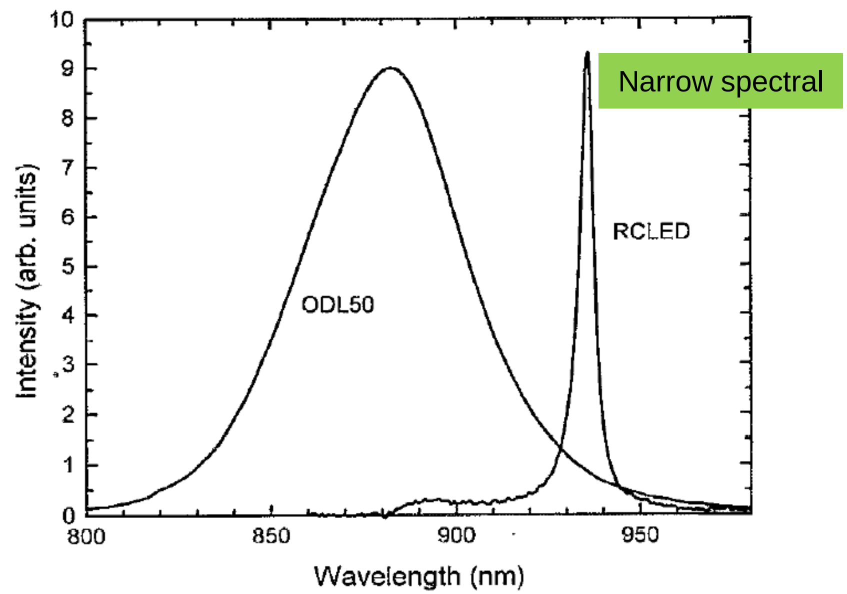
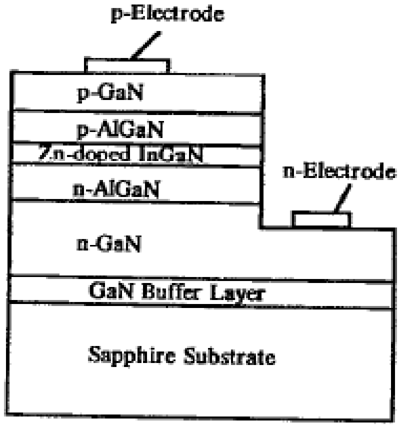


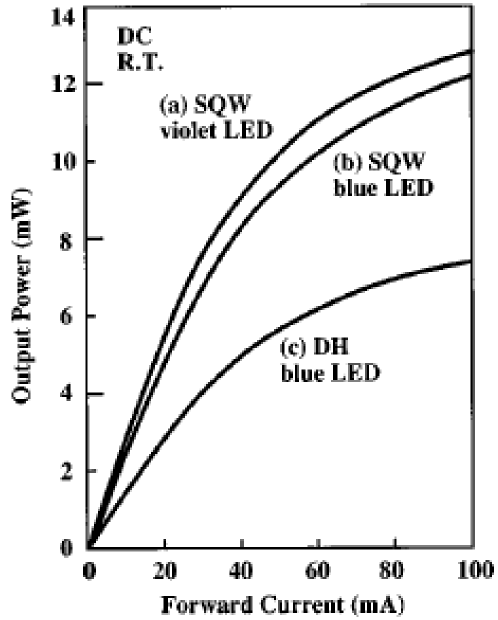
FIG. 3. A comparison of the spectral shapes of an RCLED and a reference ODL50 light emitting diode (LED) coupled into a 62.5 μm core graded-index multimode fiber. The RCLED has a spectral width of about 5 nm, while the ODL50 has a spectral width of 50 nm.

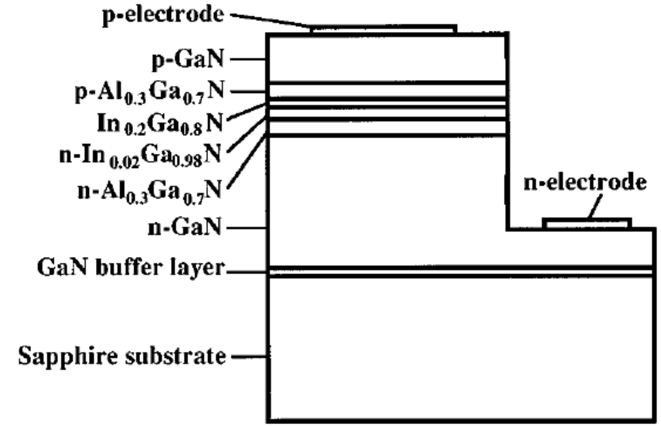
QW LED for lighting



Appl. Phys. Lett. 64 (13), 28 March 1994

FIG. 1. The structure of the InGaN/AlGaN double-hetero LED.





Appl. Phys. Lett. **67** (13), 25 September 1995

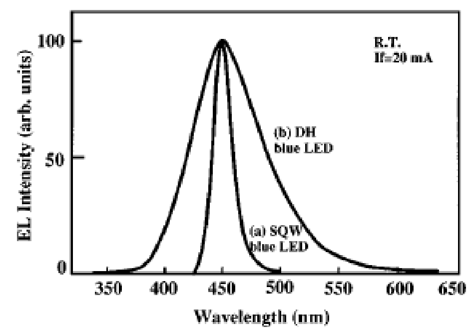
FIG. 1. The structure of SQW blue LED.

Thin layer of InGaN ~ 50 nm.
External quantum efficiency, EQE is 2.7% at 20mA

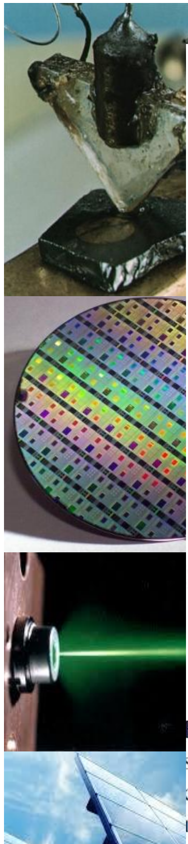
$$EQE = \frac{injected \quad electrons/s}{emitted \quad photons/s}$$

This was a key breakthrough. Shuji Nakamura was credited for this blue LED breakthrough.

QW design replaces the double heterostructure design.
$In_{0.2}Ga_{0.8}N$ ~ 2 nm sandwiched between $In_{0.02}Ga_{0.98}N$.
Much higher output power produced.



Advanced LED structures for lighting



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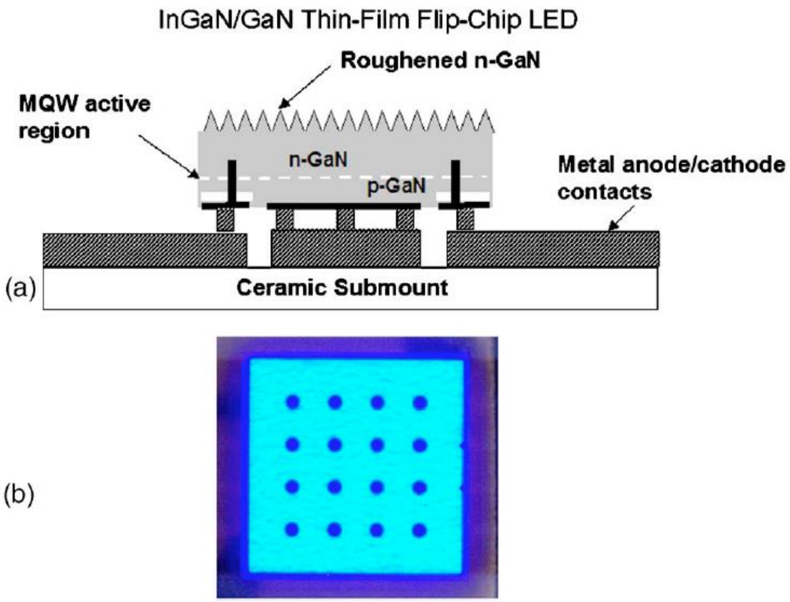
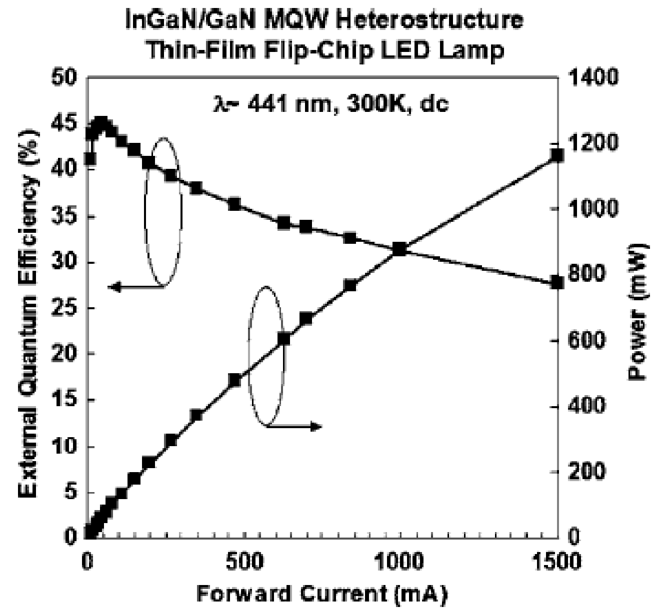
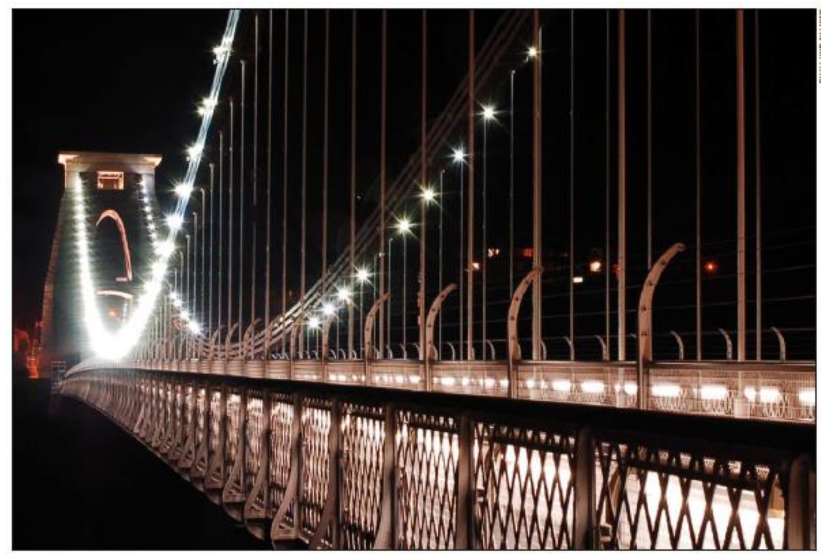


FIG. 1. (Color online) (a) Schematic cross-sectional representation of the structure of InGaN/GaN thin-film flip-chip LED. Same-sided anode and cathode are shown connected with gold interconnects to the ceramic submount. (b) Plan view photomicrograph of the device in operation.

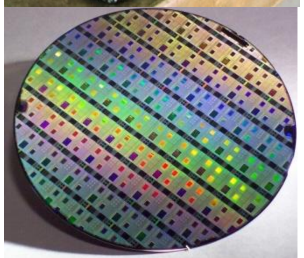
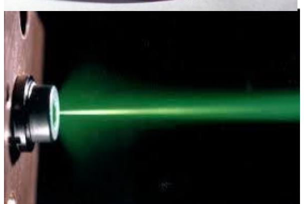


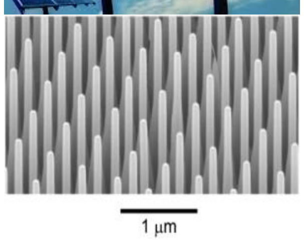
Rough GaN disrupts waveguiding action, so output power increases. Also helps to guide the light vertically.
No top contact.
Use of MQW increases the output power.
Mounted on high thermal conductivity submount.
Growth substrate is removed.

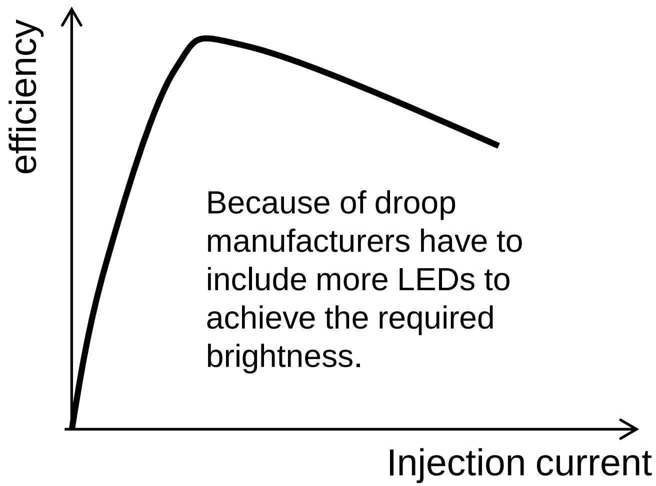


Philips Lumileds' Luxeon LED chips, which incorporate a flip-chip design, already illuminate architectural attractions such as the Clifton Suspension Bridge in Bristol, UK, completed in 1864. The addition of the thin-film technology to Luxeon products will take the performance to a new level and help to initiate penetration into the residential-lighting market.

Remember droop?





Because of droop manufacturers have to include more LEDs to achieve the required brightness.

In GaAs LEDs this droop has been attributed to heating effects that enable carriers to escape from the active region and hence reduce radiative recombination.
However in white LEDs, many mechanisms have been proposed as the cause of droop in white LEDs

Mechanisms suggested include

i) Defect free regions are saturated at high current, such that injected carriers spill over to regions with defects and hence recombine non-radiative. This was attributed to In-rich cluster with low defects, deduced from bright images in electron microscopes.

ii) Idea (i) demonstrated to be due to artifact of electron microscope.

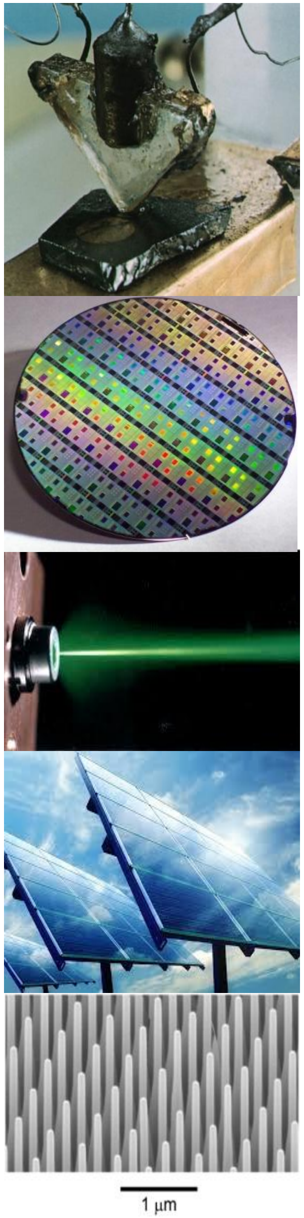
iii) Auger recombination was proposed. Deduced by fitting the photo luminescence data.

iv) Carrier leakage, i.e carrier escaping from the “quantum well” active region.

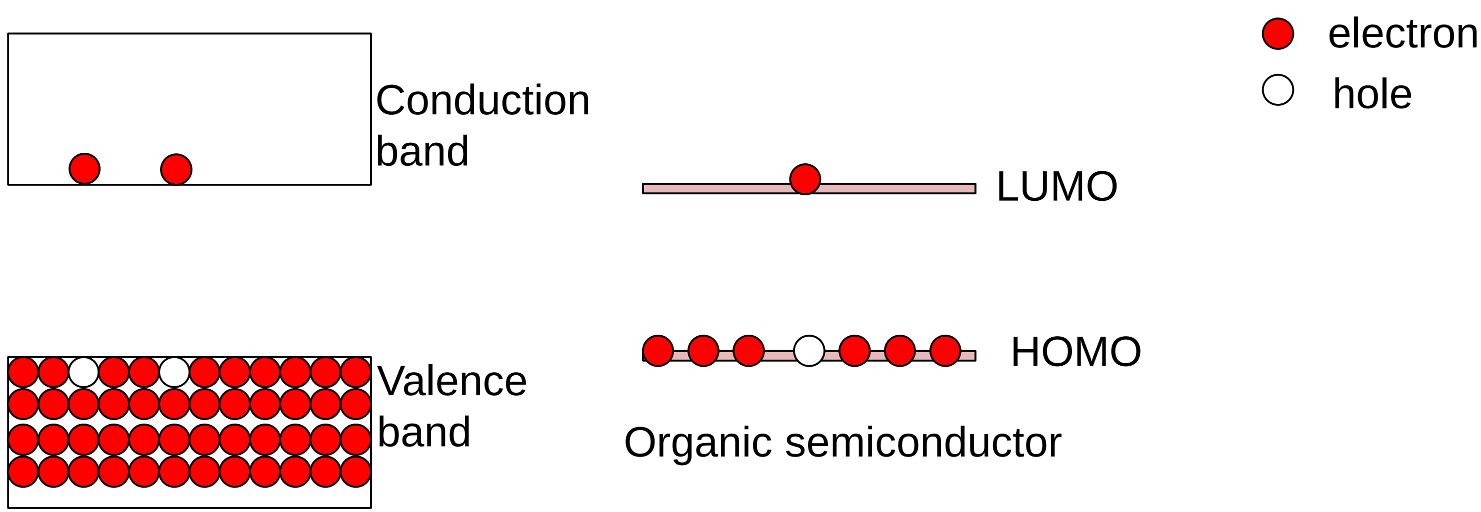
The debate continues…..

http://spectrum.ieee.org/semiconductors/optoelectronics/the-leds-dark-secret
http://spectrum.ieee.org/semiconductors/optoelectronics/a-definitive-explanation-for-led-droop

Organic Semiconductor



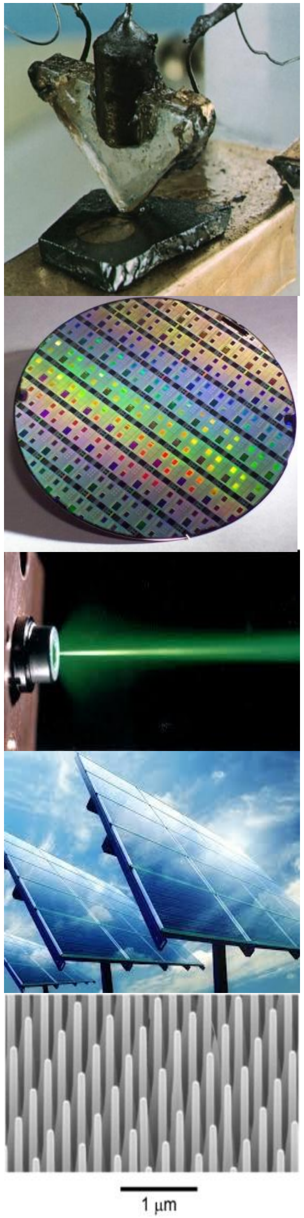
In organic semiconductors the nature of the atomic bonding produces conduction and valence bands. In organic semiconductor (polymers with long chains of molecule), if there is a good fit between the molecules, the material can crystallised (although not as good as traditional semiconductors). The ordering in the molecule leads to a narrow range of allowed energy that can be better described as discrete levels.
The highest occupied molecular orbital (HOMO) and the lowest unoccupied molecular orbital (LUMO) can be thought of as the equivalence of the valence and conduction bands, respectively.

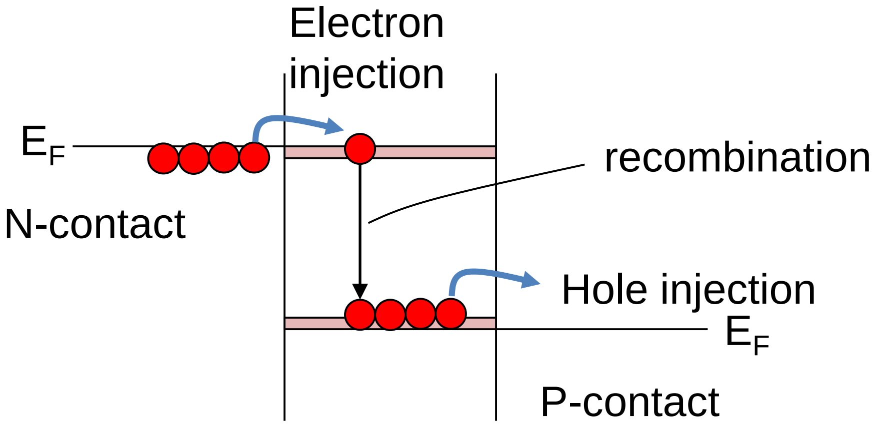


Conventional semiconductor

Organic semiconductor

Organic diode



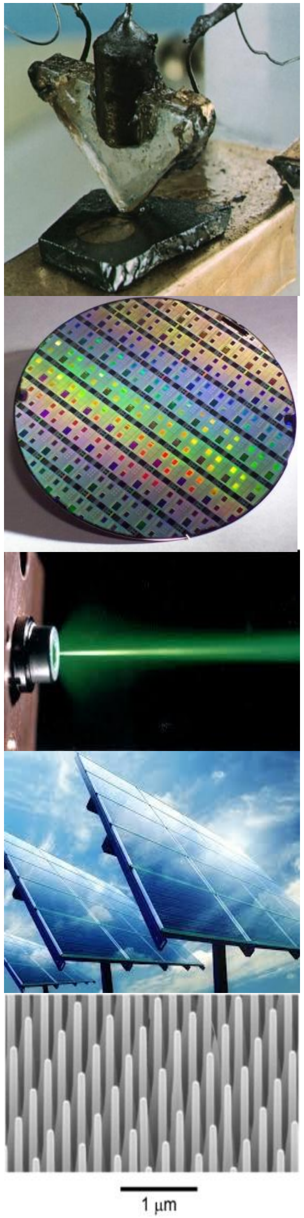


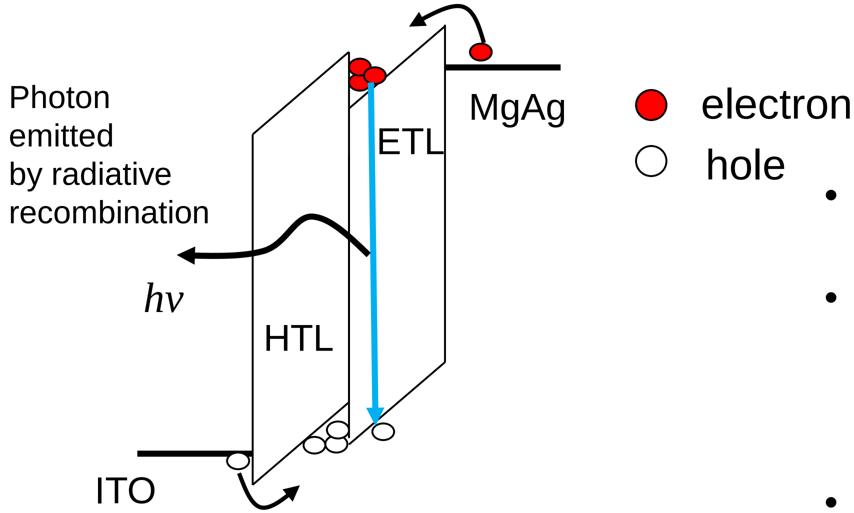
Approximately 25% of the transitions are radiative recombination. Therefore it is possible to fabricate an LED using an appropriate organic semiconductor and two metal contacts with suitable Fermi levels as shown on the left.

We know that Carbon can be in insulating form (diamond) or in conductive form (graphite). Likewise polymers C_xH_y can also be conductive or insulting.

Six Benzene (C_6H_6) molecular rings can be combined with a central Al atom to form AlQ_3, a layer with an electron-deficient state that acts as electron transport layer (ETL).
When six benzene rings are combined with nitrogen atoms, a diamine layer which can accept hole and acts as hole transport layer (HTL).

Organic LED (OLED)





- The layers (~75nm) are thin to allow low bias voltage
- Small barrier height between metal and organic semiconductor to allow efficient carrier injection.
- Proper bandgap to achieve the require emission wavelength.

A basic structure of organic LED (OLED) combines the ETL, HTL with n-contact (MgAg alloy) and p- contact (transparent Indium Tin Oxide, ITO). Under bias electrons are injected from the n-contact, transported by EML to the AlQ_3/diamine heterojunction. Likewise holes are injected by the p-contact and transported to the junction via HML. At the junction the barriers trapped the electrons and holes to increase the probability of radiative recombination.