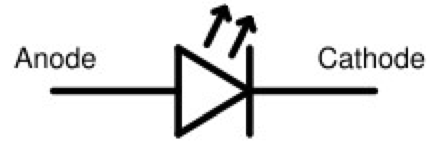
Optoelectronics

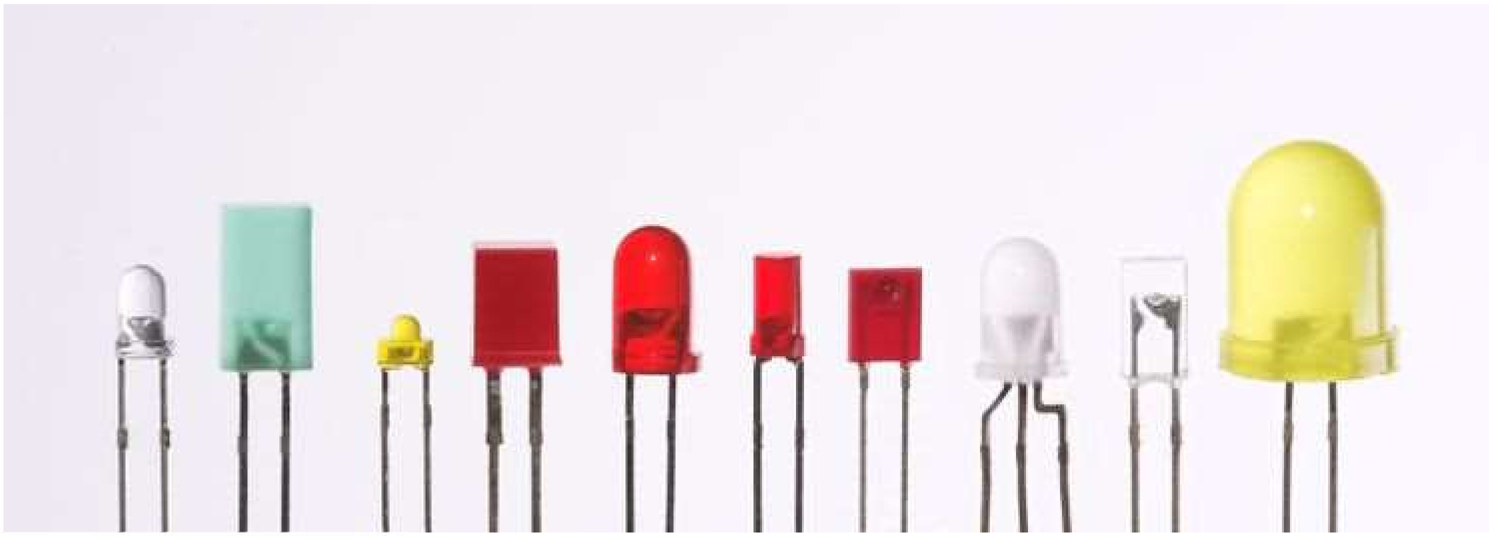
Optoelectronics

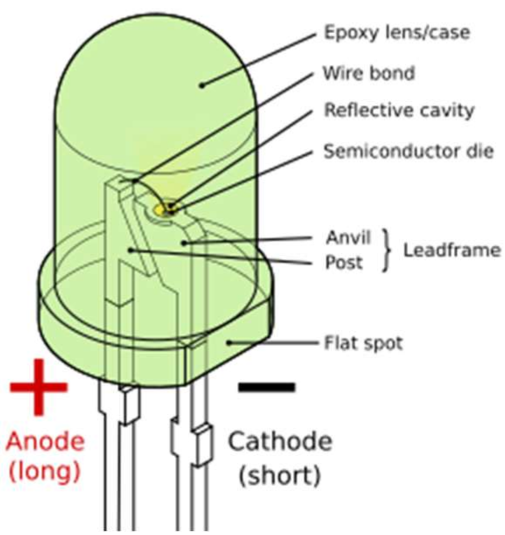
light emitting diode
laser diode
solar cell
photo detectors

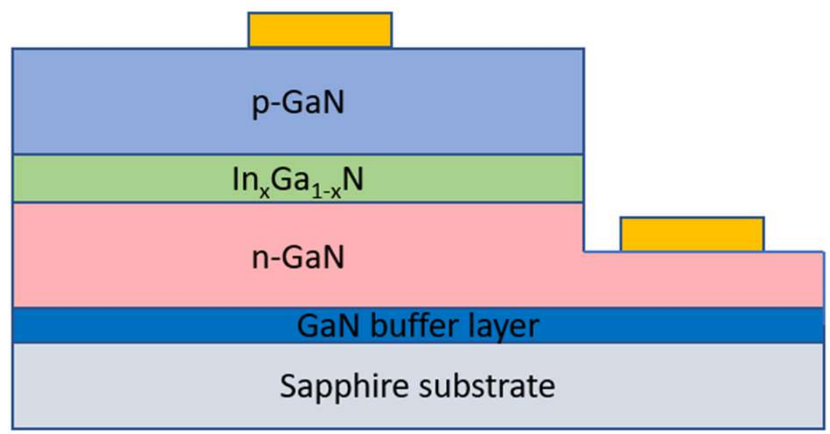
communications, memory (DVD), displays, printing, bar-code readers, solar energy, lighting, laser surgery, measurement, guidance, spectroscopy, LiFi

Light emitting diodes





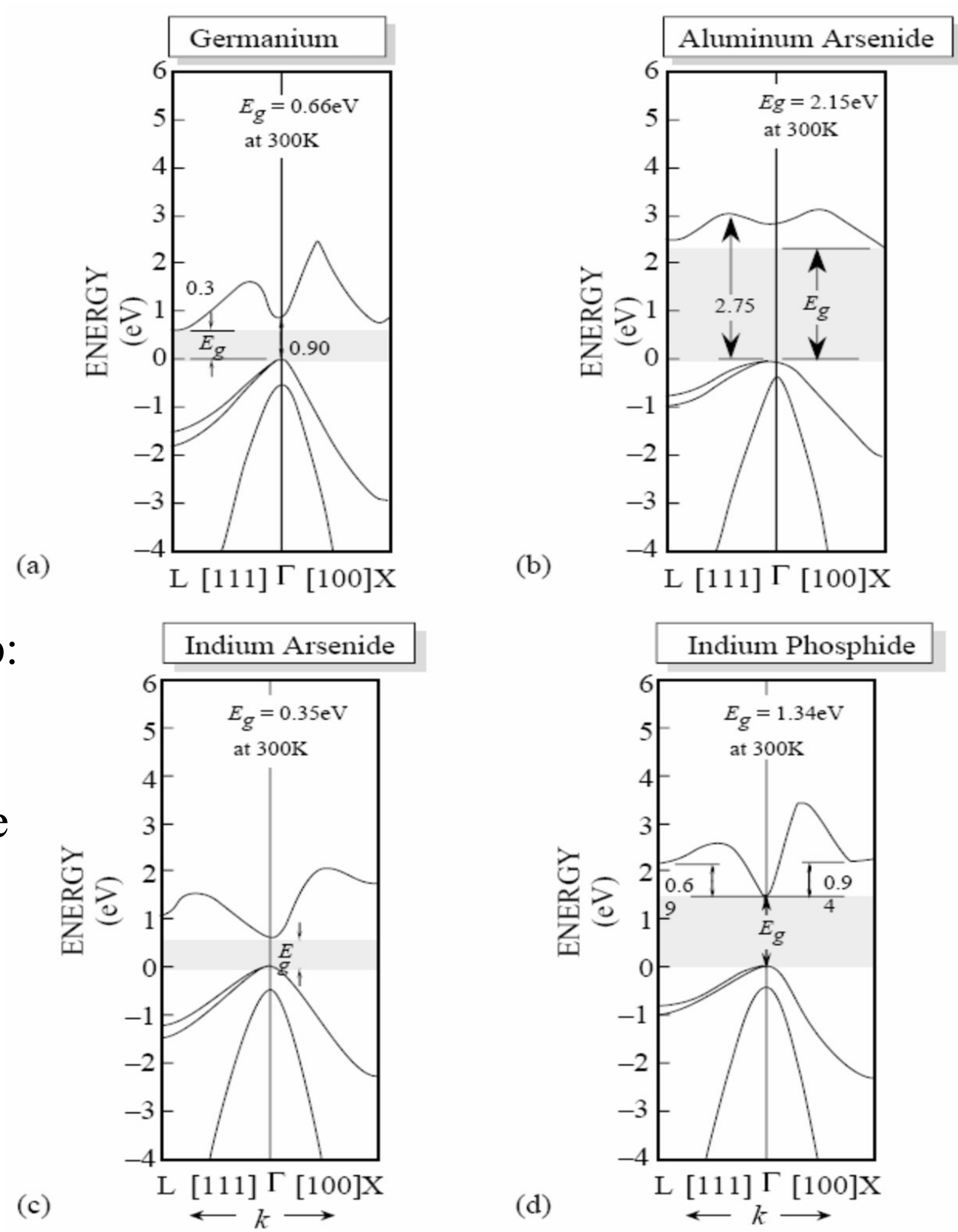




Solid state lighting is efficient.

direct bandgap:
$\Delta k = 0$

photons can be emitted



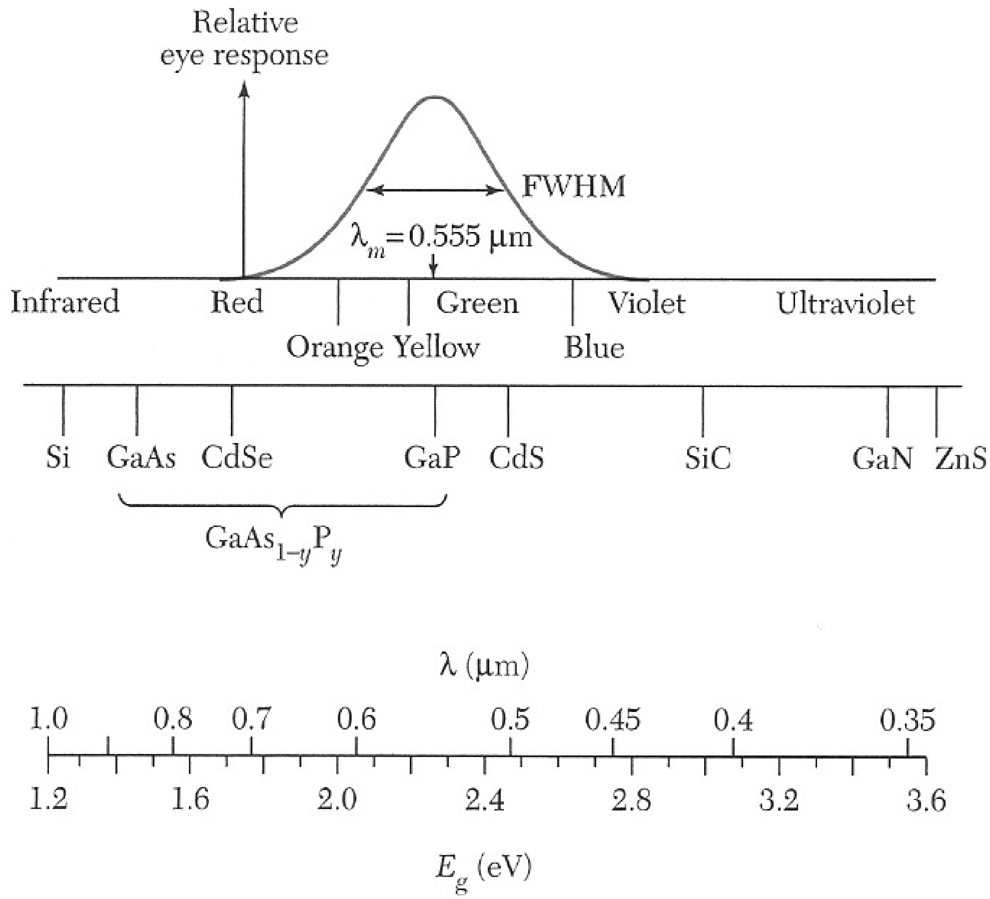
indirect bandgap:
$\Delta k \neq 0$

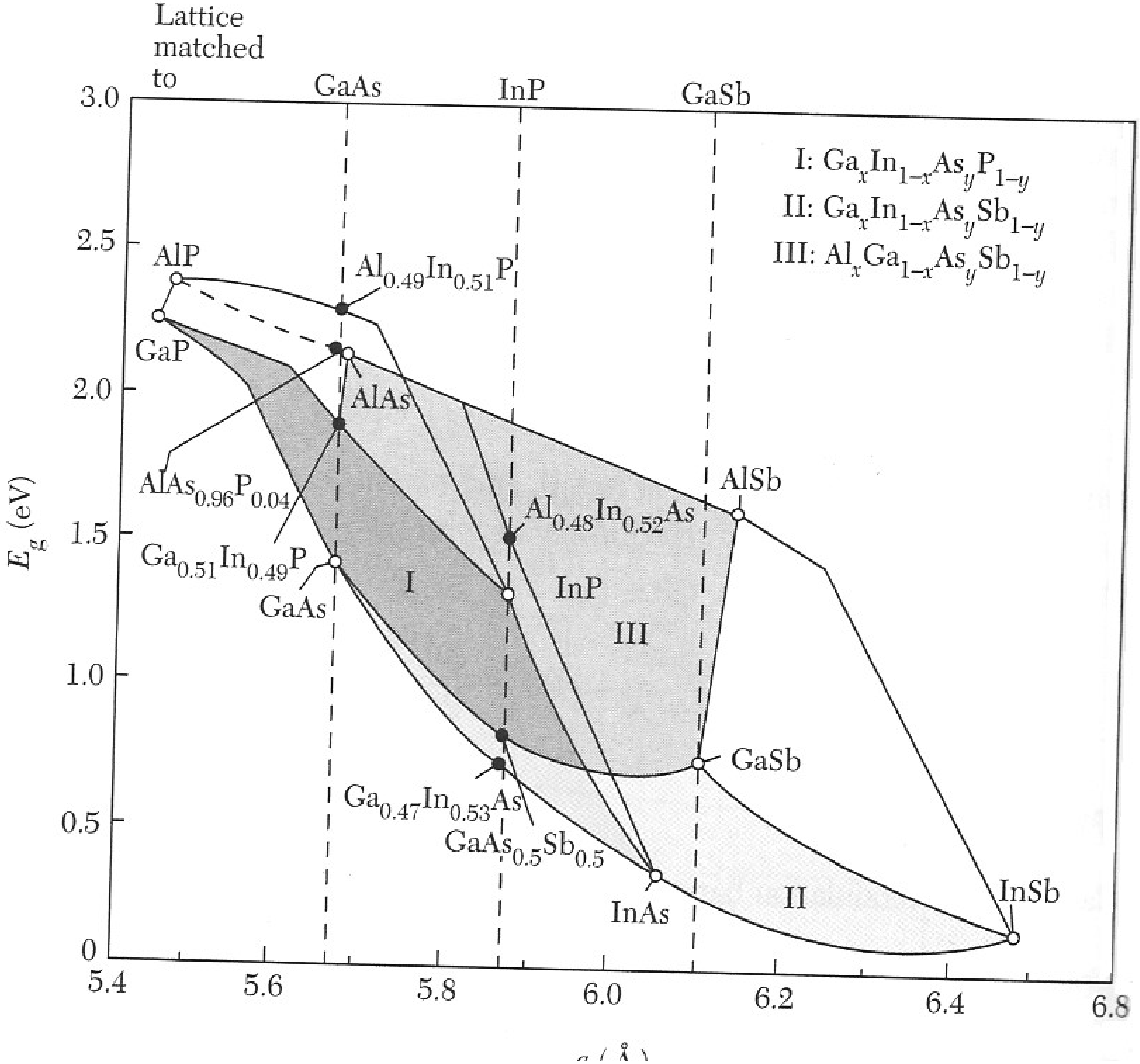
phonons are emitted

Light emitting diodes

TABLE 1 Common III-V materials used to produce LEDs and their emission wavelengths.

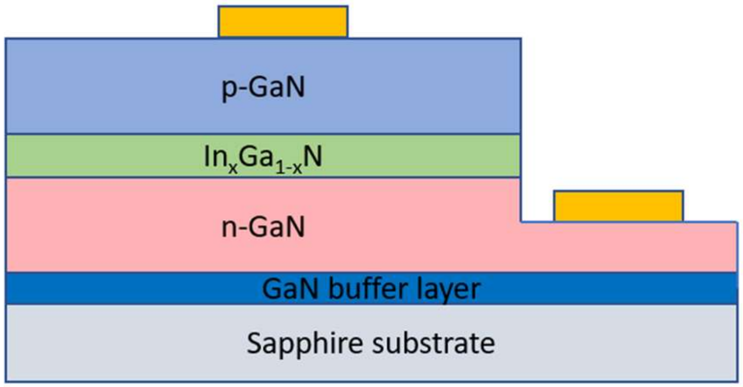
Material	Wavelength (nm)
InAsSbP/InAs	4200
InAs	3800
GaInAsP/GaSb	2000
GaSb	1800
$Ga_xIn_{1-x}As_{1-y}P_y$	1100-1600
$Ga_{0.47}In_{0.53}As$	1550
$Ga_{0.27}In_{0.73}As_{0.63}P_{0.37}$	1300
GaAs:Er,InP:Er	1540
Si:C	1300
GaAs:Yb,InP:Yb	1000
$Al_xGa_{1-x}As$:Si	650-940
GaAs:Si	940
$Al_{0.11}Ga_{0.89}As$:Si	830
$Al_{0.4}Ga_{0.6}As$:Si	650
$GaAs_{0.6}P_{0.4}$	660
$GaAs_{0.4}P_{0.6}$	620
$GaAs_{0.15}P_{0.85}$	590
$(Al_xGa_{1-x})_{0.5}In_{0.5}P$	655
GaP	690
GaP:N	550-570
$Ga_xIn_{1-x}N$	340,430,590
SiC	400-460
BN	260,310,490

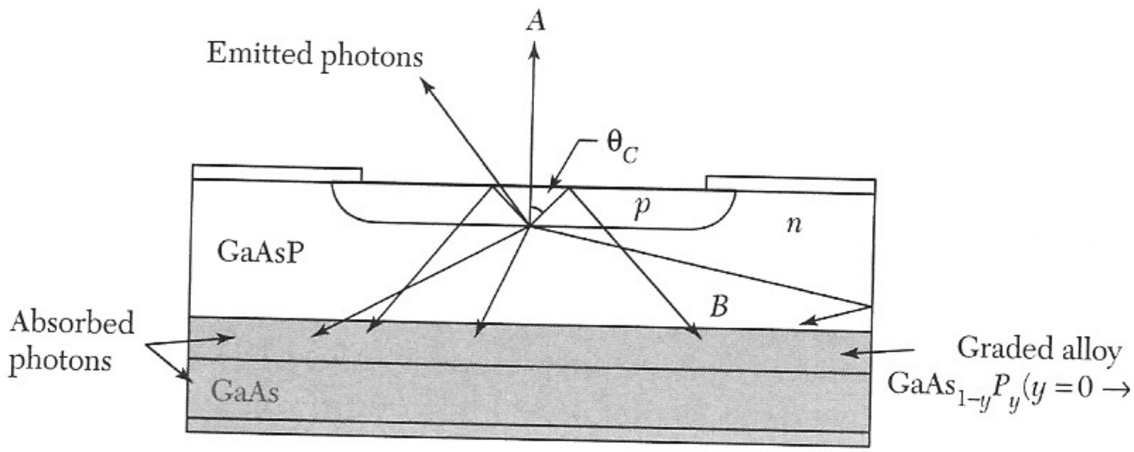


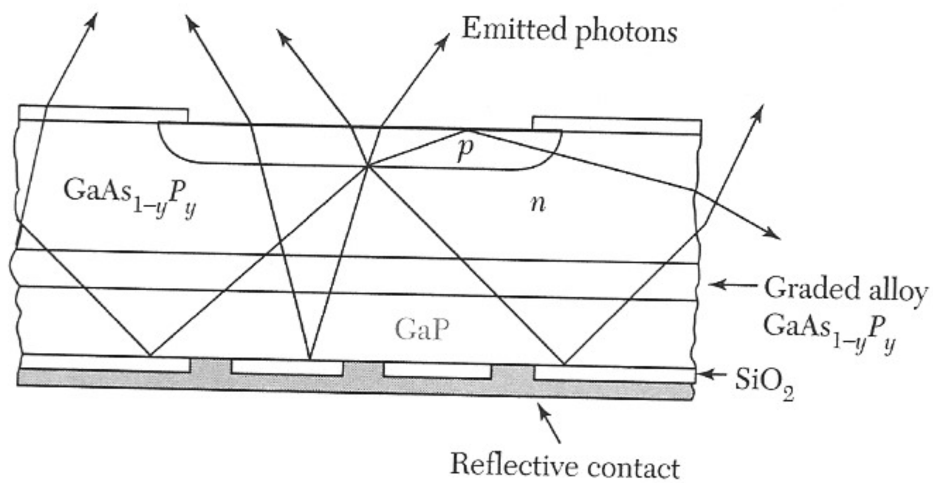


Lattice matched to
GaAs
InP
GaSb
I: $Ga_xIn_{1-x}As_yP_{1-y}$
II: $Ga_xIn_{1-x}As_ySb_{1-y}$
III: $Al_xGa_{1-x}As_ySb_{1-y}$
AlP
GaP
$Al_{0.49}In_{0.51}P$
AlAs
$AlAs_{0.96}P_{0.04}$
$Ga_{0.51}In_{0.49}P$
GaAs
I
InP
III
$Al_{0.48}In_{0.52}As$
AlSb
GaSb
$Ga_{0.47}In_{0.53}As$
$GaAs_{0.5}Sb_{0.5}$
InAs
II
InSb
E_g (eV)
3.0
2.5
2.0
1.5
1.0
0.5
0
5.4
5.6
5.8
6.0
6.2
6.4
6.8

Light emitting diodes







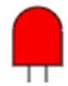
absorption
reflection
total internal reflection

Light Emitting Diode

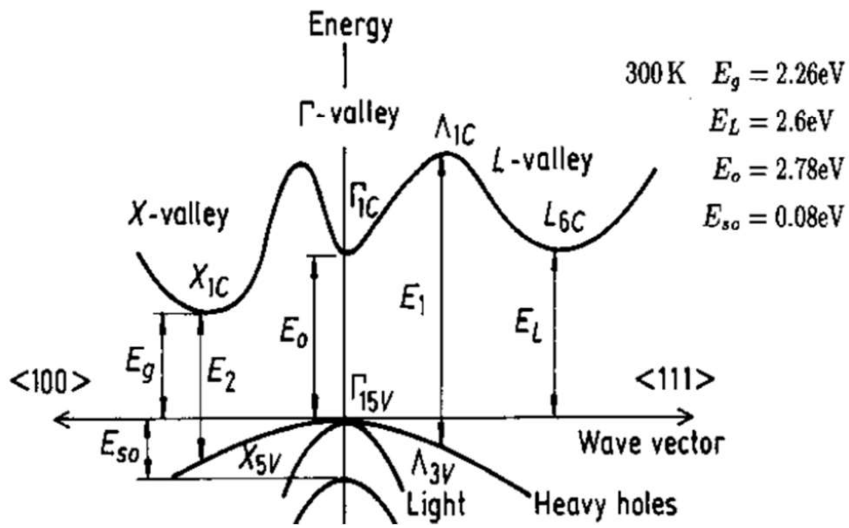
A Light Emitting Diode (LED) consists of a pn-diode in a semiconductor with a direct bandgap. When the diode is forward biased, the electrons and the holes are pushed towards the junction where they recombine. The photons that are emitted have the energy of the band gap, $E_g = \frac{hc}{\lambda}$. The slider below lets you select a wavelength. The corresponding bandgap to this wavelength is calculated and the approximate color is shown. For some bandgap energies, the composition of a direct bandgap semiconductor that will emit this wavelength is shown.

λ = 650 nm - + $Al_{0.39}Ga_{0.61}As$ $GaAs_{0.39}P_{0.61}$

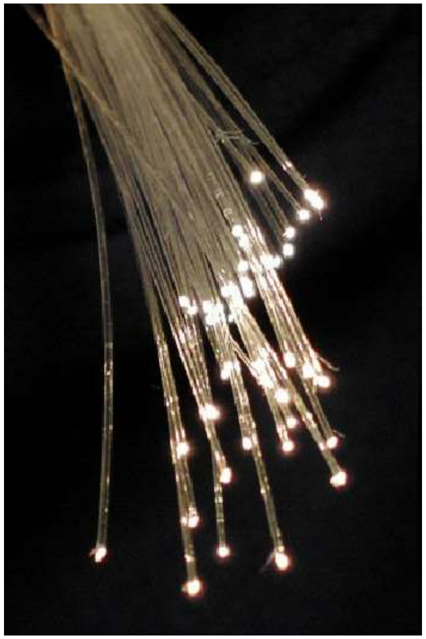
E_g = 1.91 eV visible

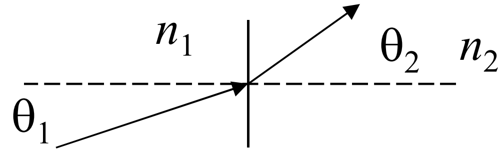


Below, simplified band diagrams can be displayed for some semiconductors. The electrons in the conduction band are primarily located at the minimum of the conduction band and the holes in the valence band are concentrated at the maximum of the valence band. The electrons are thermally excited up to about k_BT above the conduction band minimum and the holes are excited to about k_BT below the valence band maximum. When the electrons and holes recombine, this results in photon energies approximately in the range $E_g \pm k_BT$.

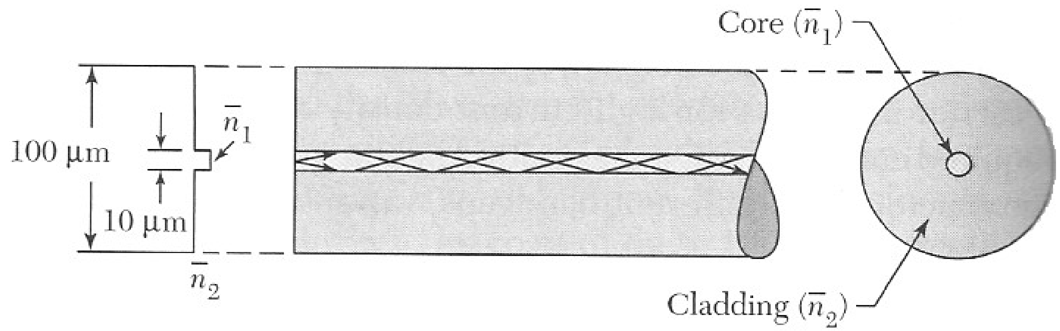


Confinement of light by total internal reflection

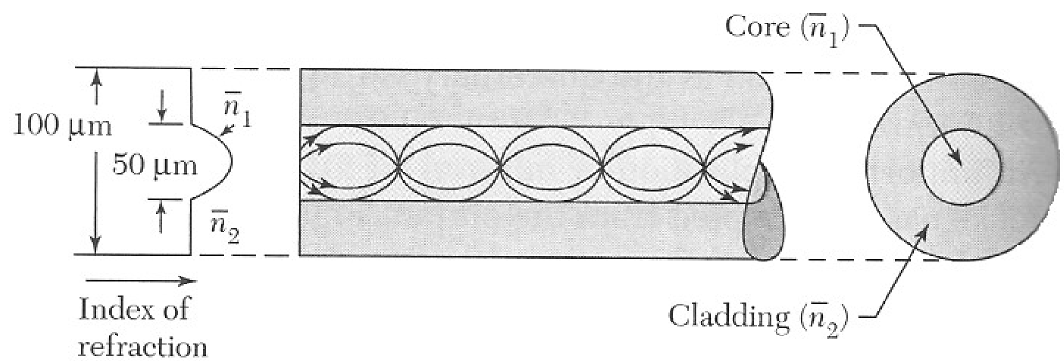


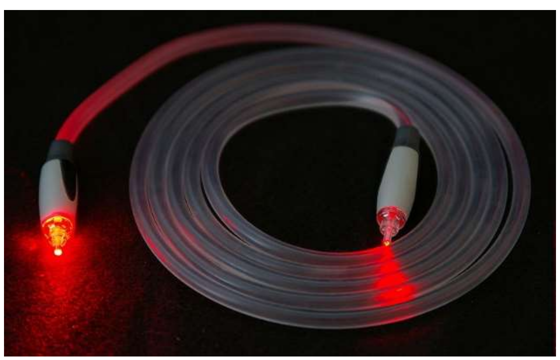


$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$



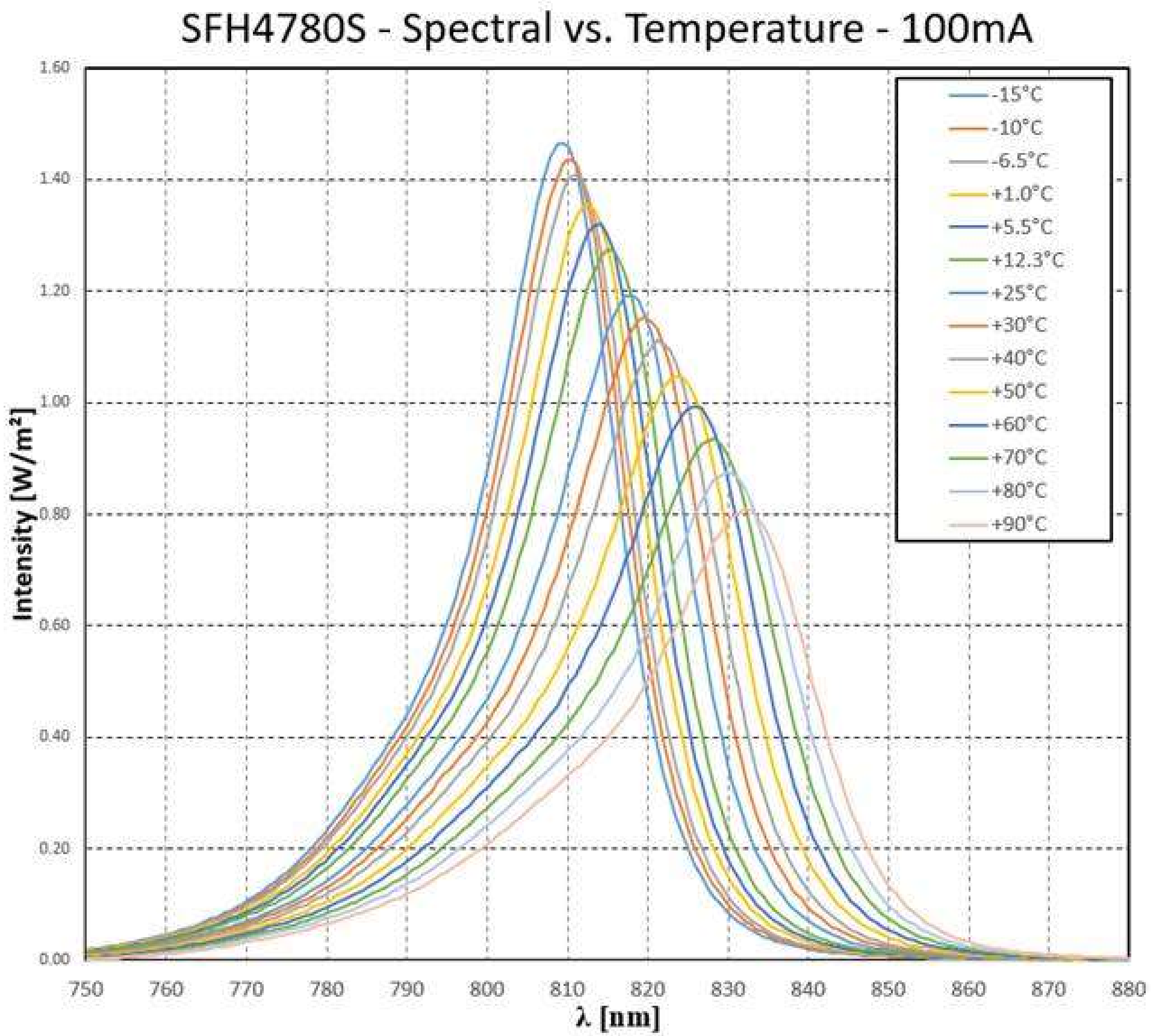
less pulse spreading for parabolically graded fiber





0.6 dB/km at 1.3 µm and 0.2 dB/km at 1.55 µm

IR LED



Measurement by Jan Enenkel

Photo detectors

Intrinsic semiconductor $\sigma = e(\mu_n n + \mu_p p)$ (used in copiers)

Unbiased pn junction - like a solar cell

Reverse biased pn junction - smaller capacitance, higher speed, less noise

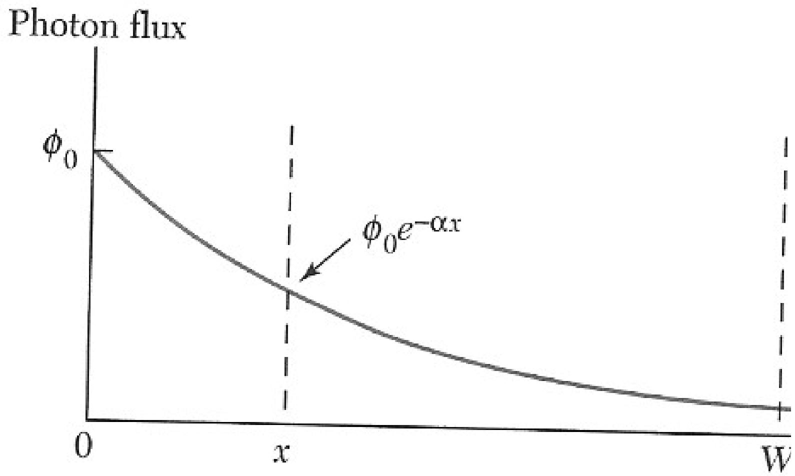
Phototransistor - light injects carriers into the base. This forward biases the emitter base junction. High responsivity.

Ambient light detectors.

Active Pixel sensors for automated parking and gesture control (uses time-of-flight to image in 3-D).

Absorption

Photon flux: $\Phi(x) = \Phi_0 e^{-\alpha x}$

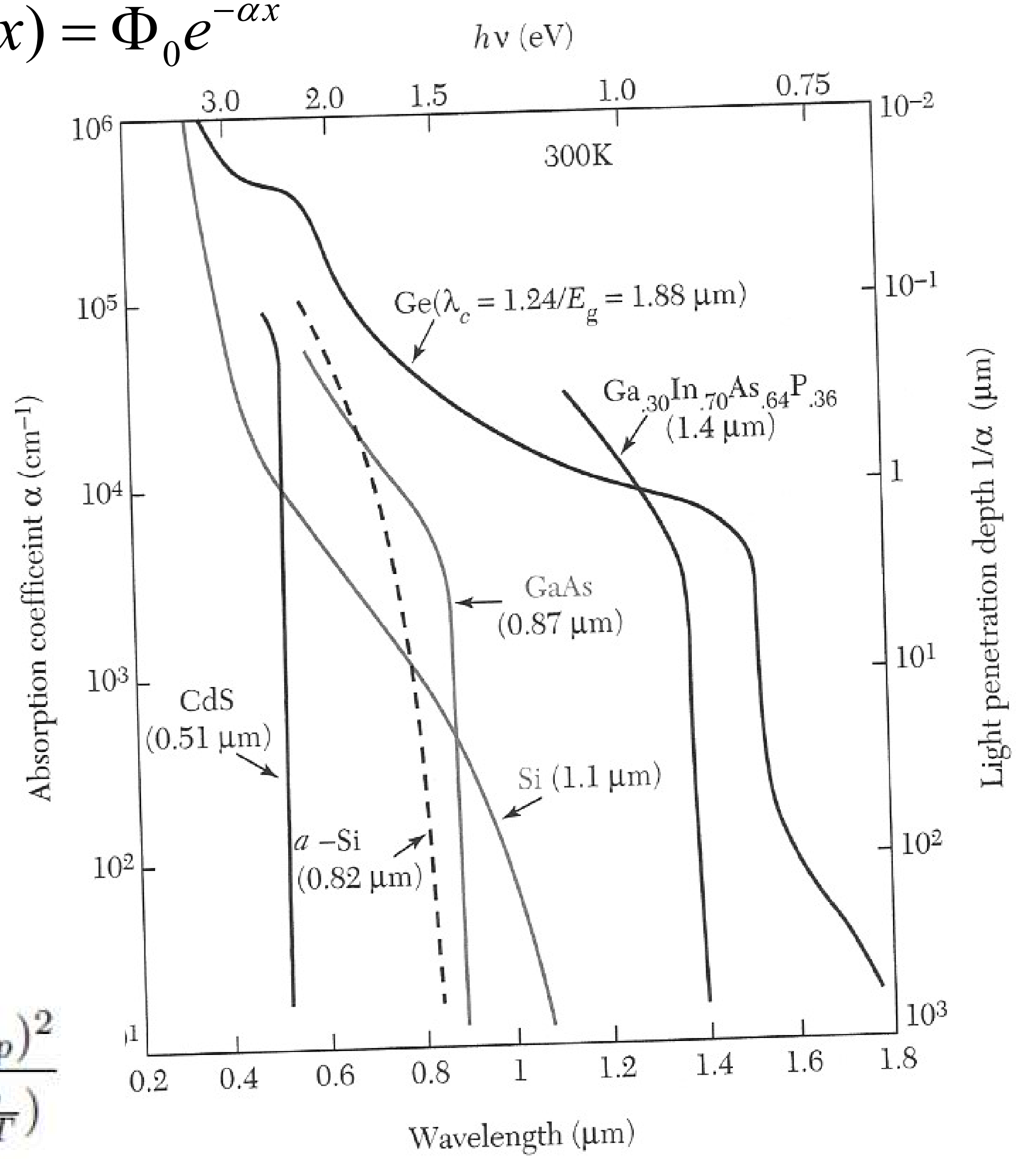


Sharp absorption edge for direct bandgap materials

$$\alpha \approx 3.5\times10^{6}\left(\frac{m_r^*}{m_0}\right)^{3/2}\frac{\sqrt{\hbar\omega - E_g}}{\hbar\omega}\quad \text{cm}^{-1}$$

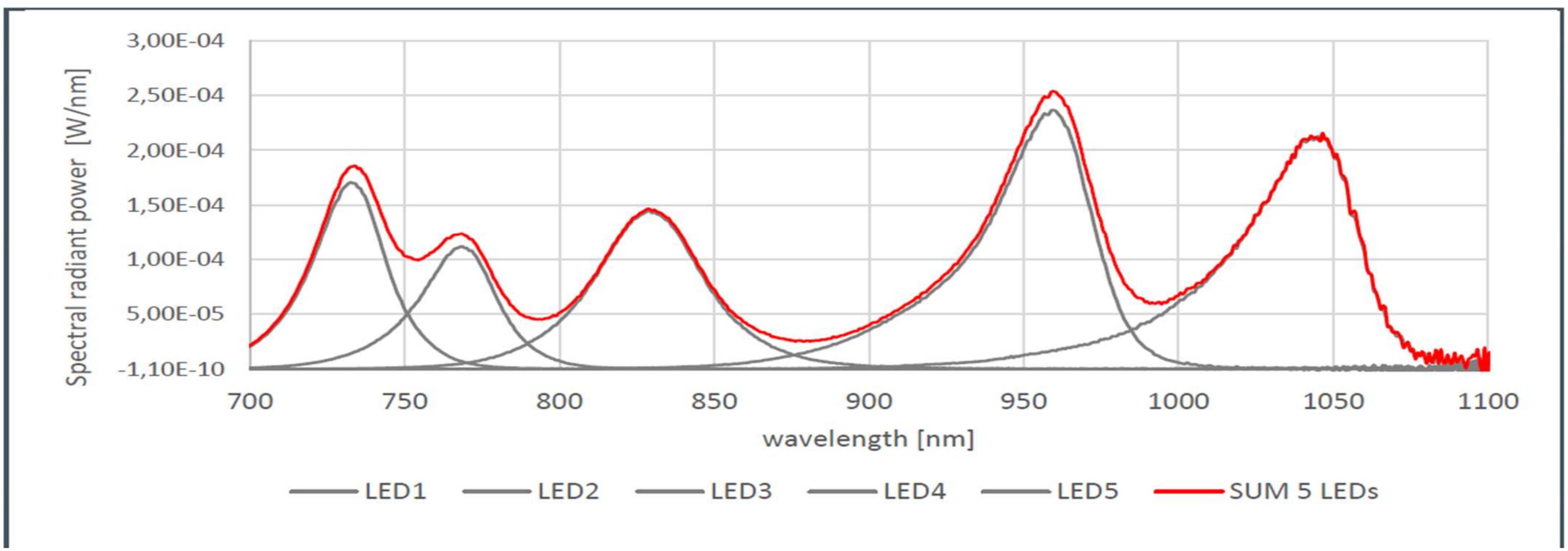
direct bandgap   indirect bandgap

$$\alpha \propto \frac{(h\nu - E_g + E_p)^2}{exp(\frac{E_p}{k_B T}) - 1} + \frac{(h\nu - E_g - E_p)^2}{1 - exp(-\frac{E_p}{k_B T})}$$

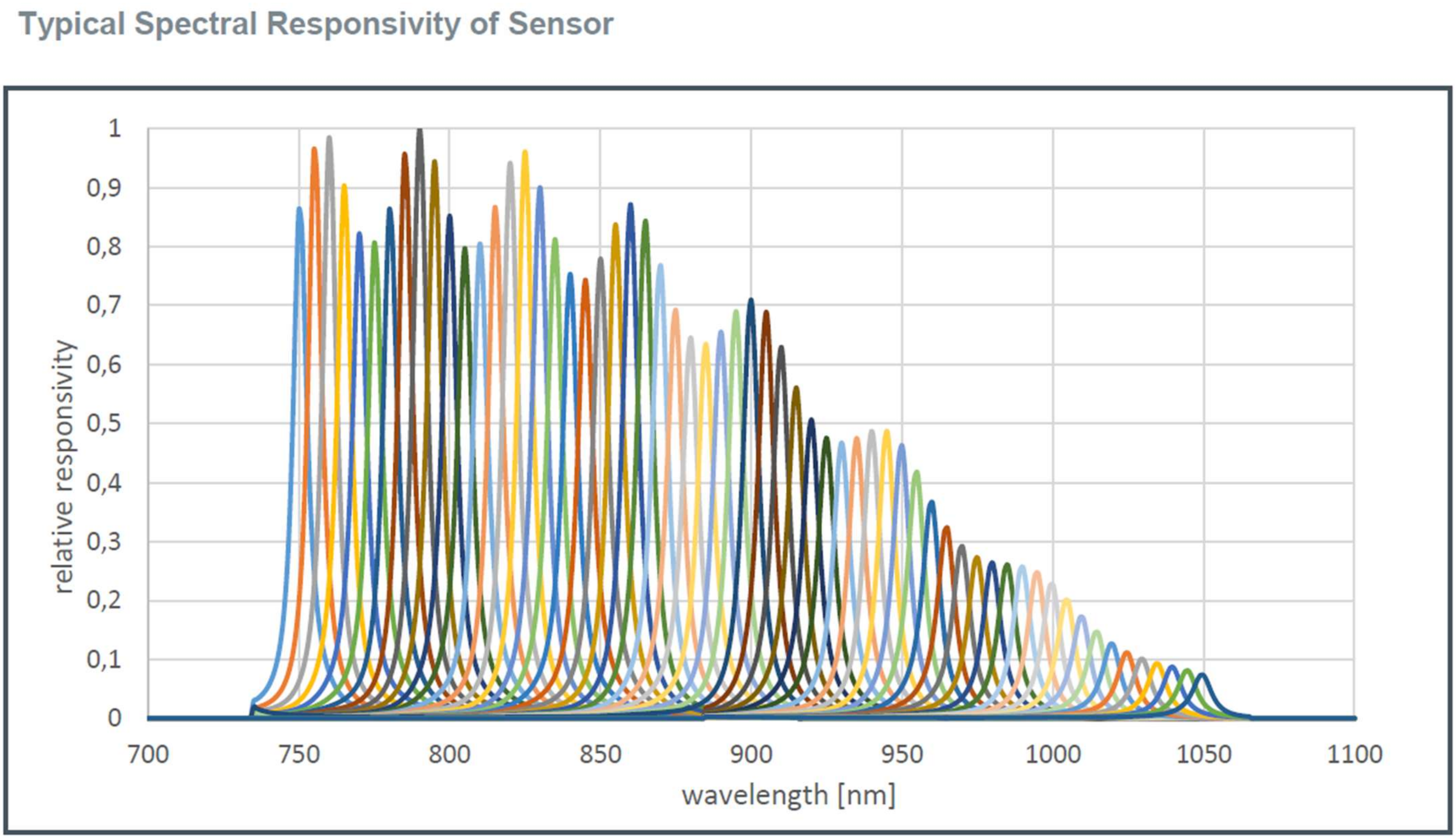


AS7420 64-channel hyperspectral near infrared sensor

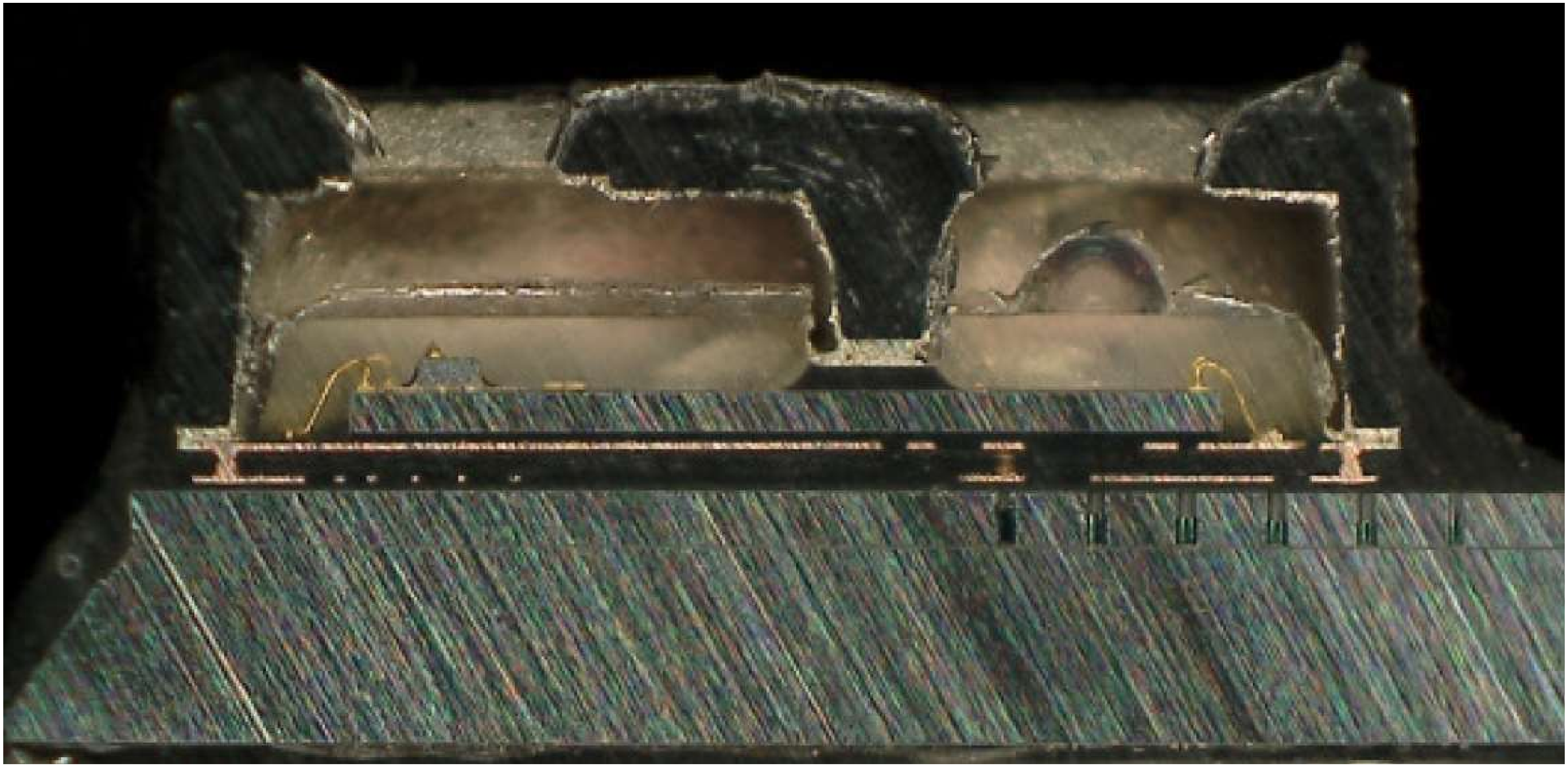
Typical LED Spectral Emission at 50mA LED current



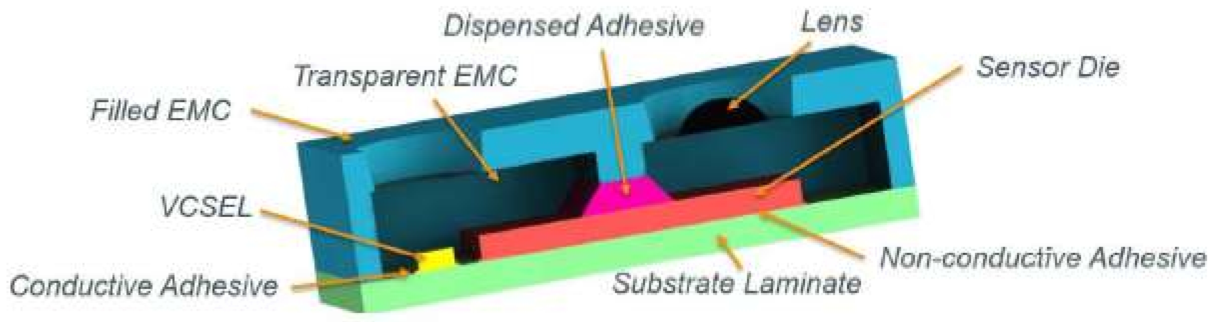
AS7420 64-channel hyperspectral near infrared sensor



Cross Section



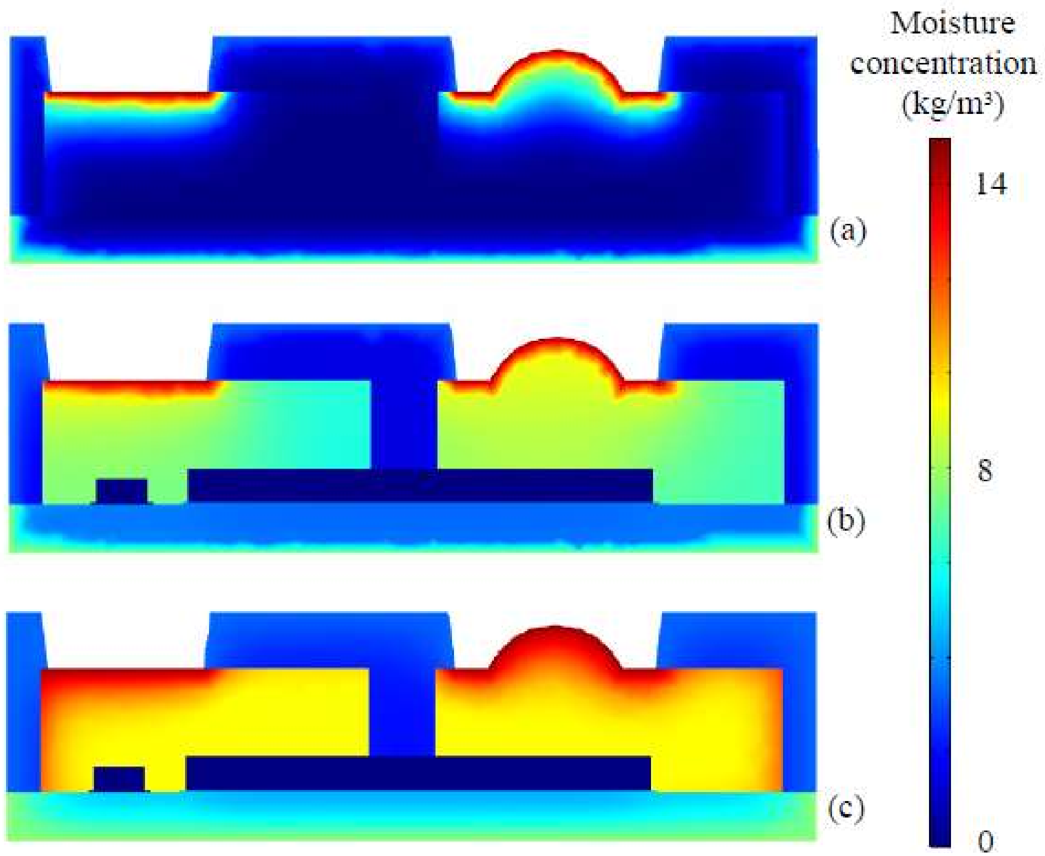
Samuel Hoermann, Master Thesis, TU Graz.



2 h

24 h

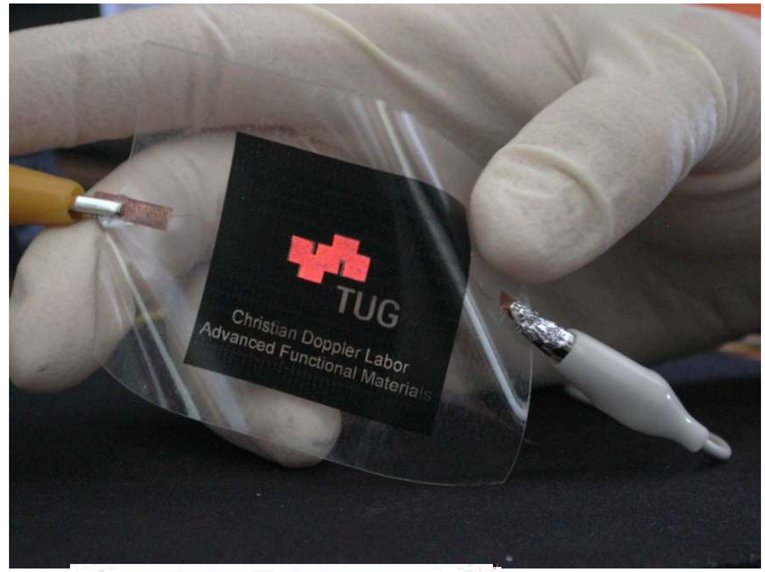
168 h

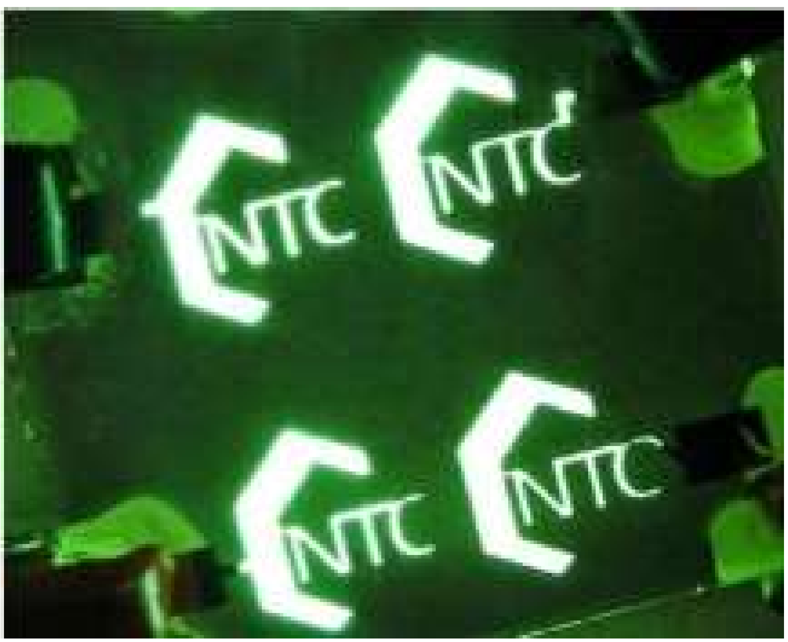


85 C / 85% RH

7th Electronic System-Integration Technology Conference (ESTC) 2018

OLEDs





Galaxy Tab

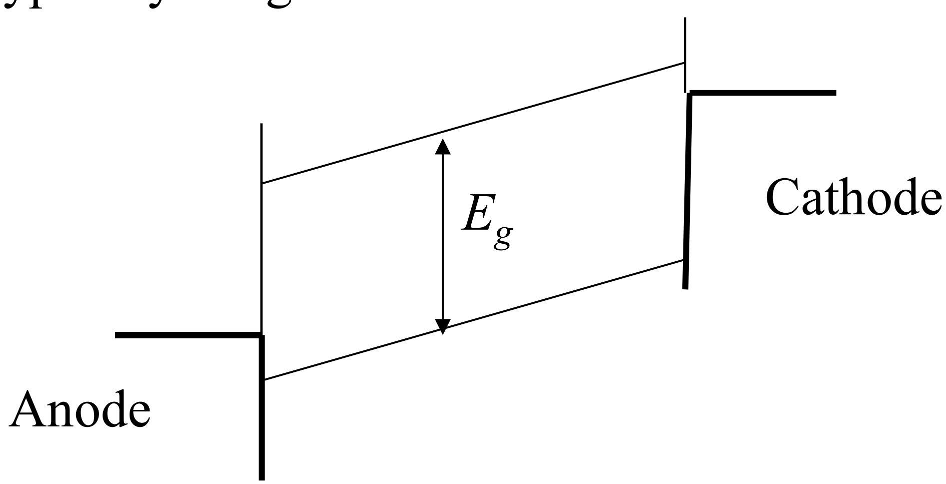
Encapsulation technology

OLEDs

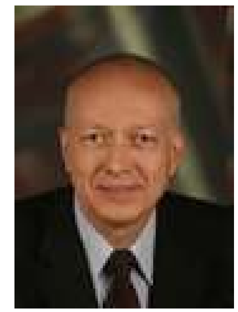
Aluminum cathode
Electron transport layer
Emission layer
Hole transport layer
ITO anode
Glass

Cathode is typically a low work function material Al, Ca - injects electrons

Anode is typically a high work function material ITO - injects holes

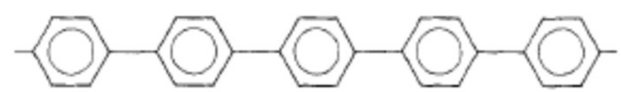


Electroluminescence in poly(p-phenylene)

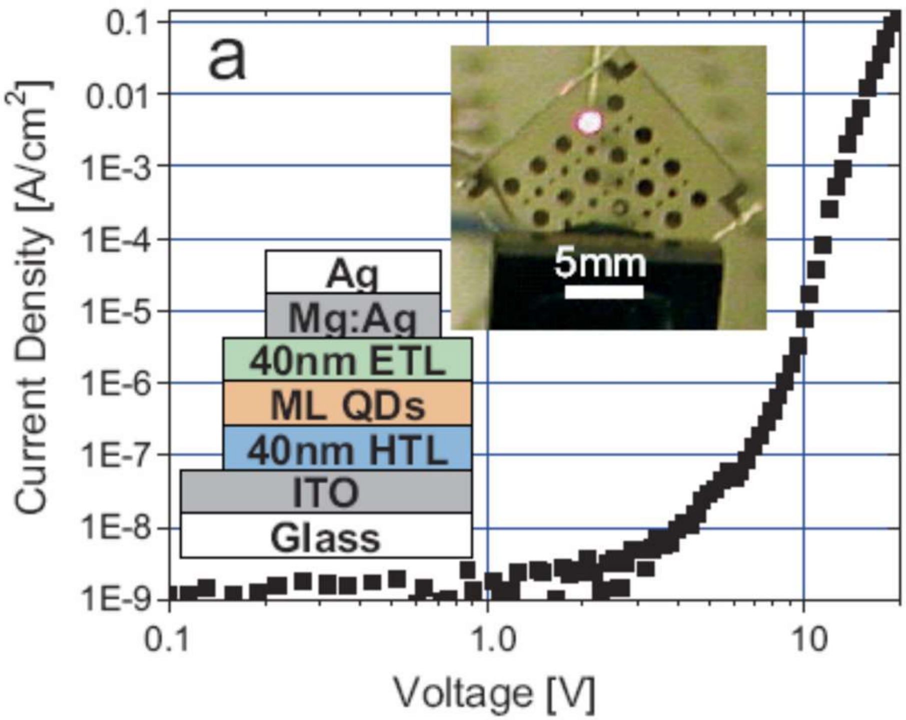


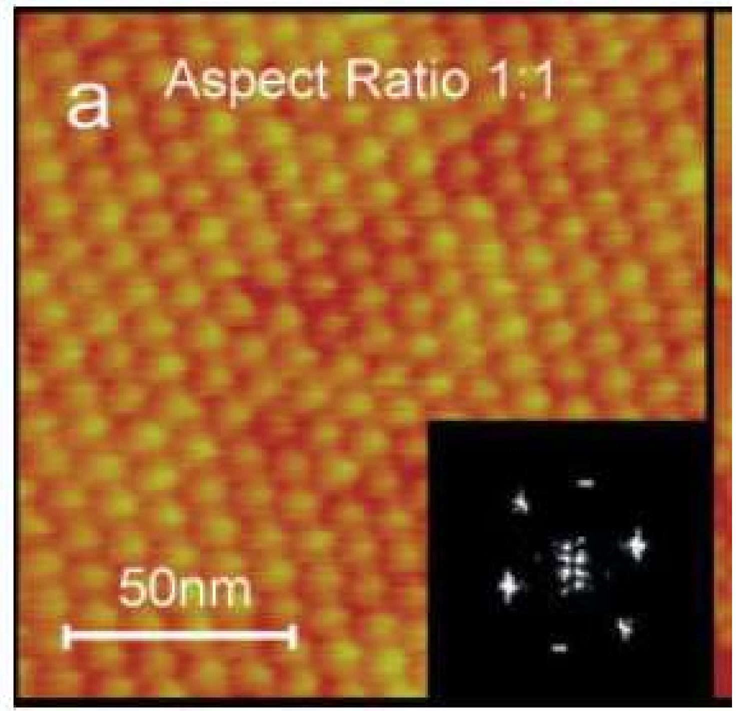
Prof. Günther Leising

In 1992, Leising et al. for the first time reported on blue electroluminescence from OLEDs containing poly(p-phenylene) (PPP).



Q-dot LEDs



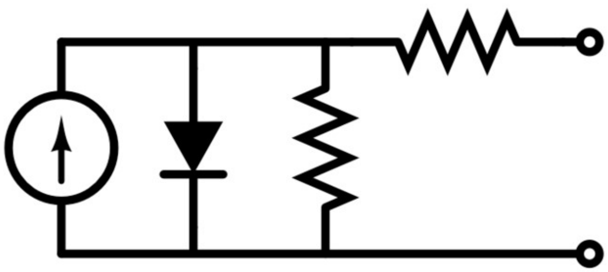


Coe-Sullivan, et al. Advanced Functional Materials, 10.1002/adfm.200400468

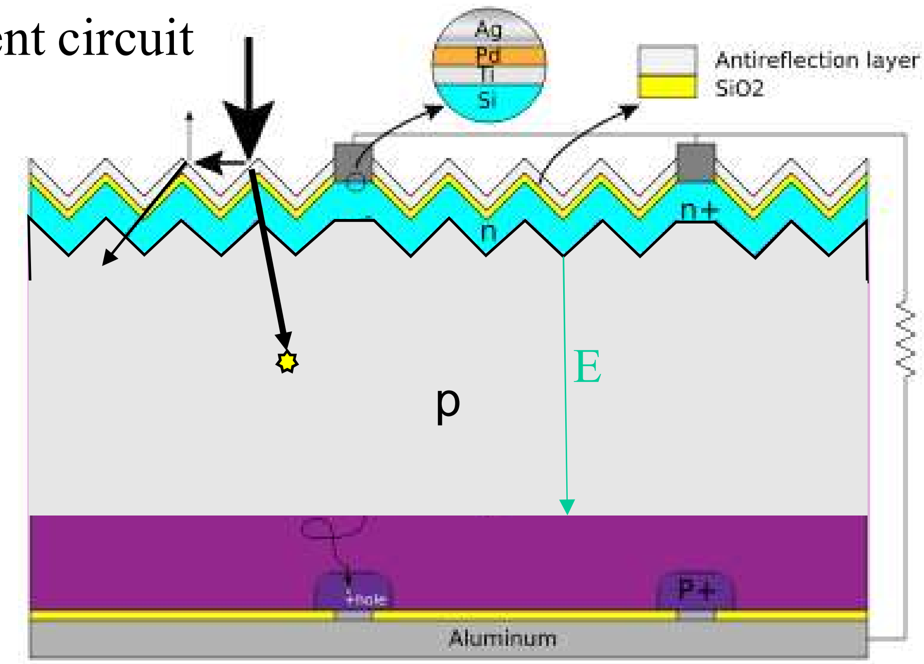
Efficient lighting

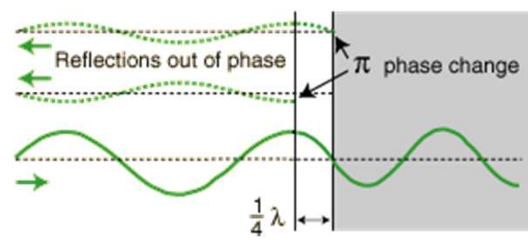
Very efficient
Many colors possible
No toxic chemicals

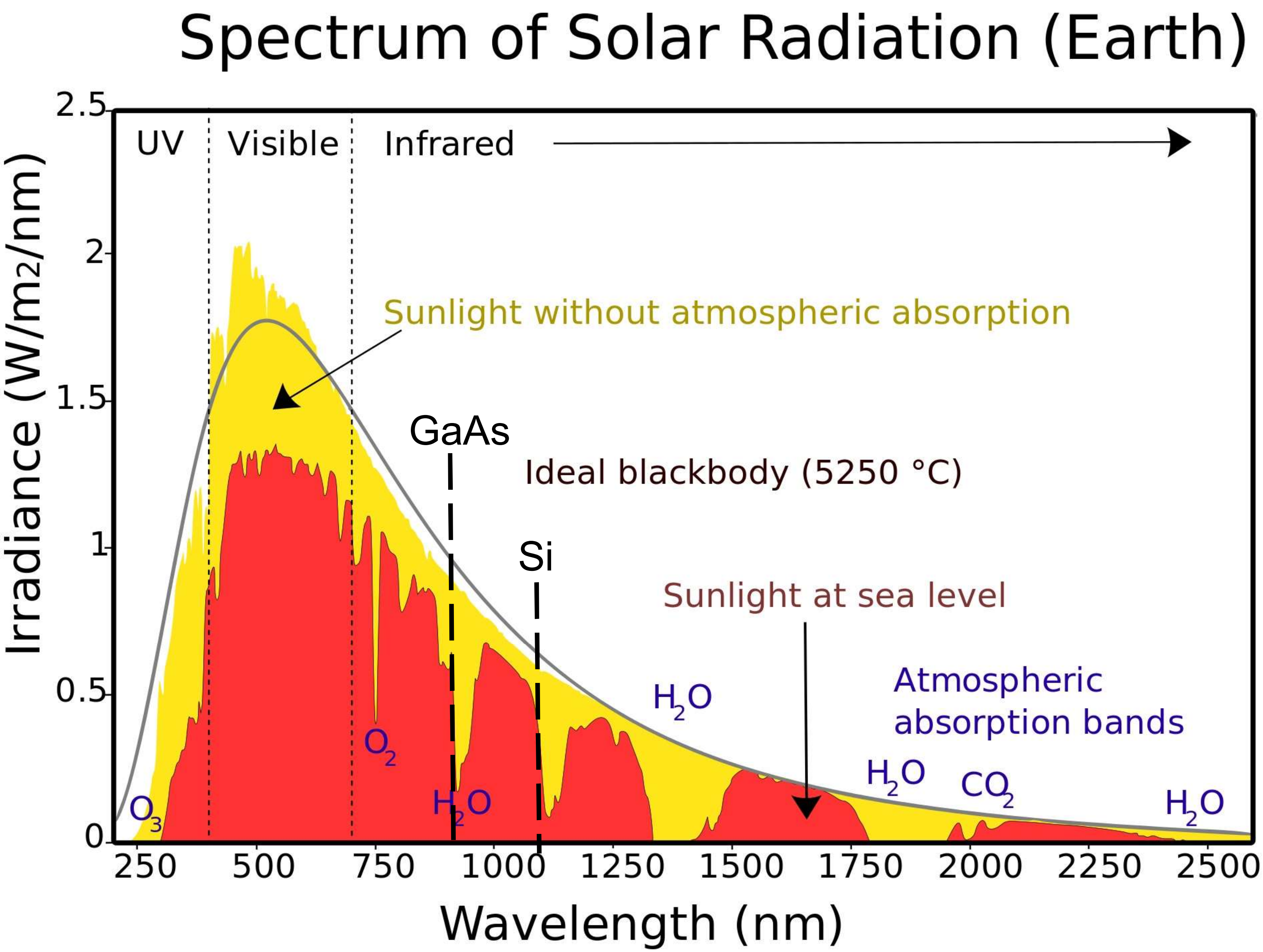
Solar cell



Equivalent circuit

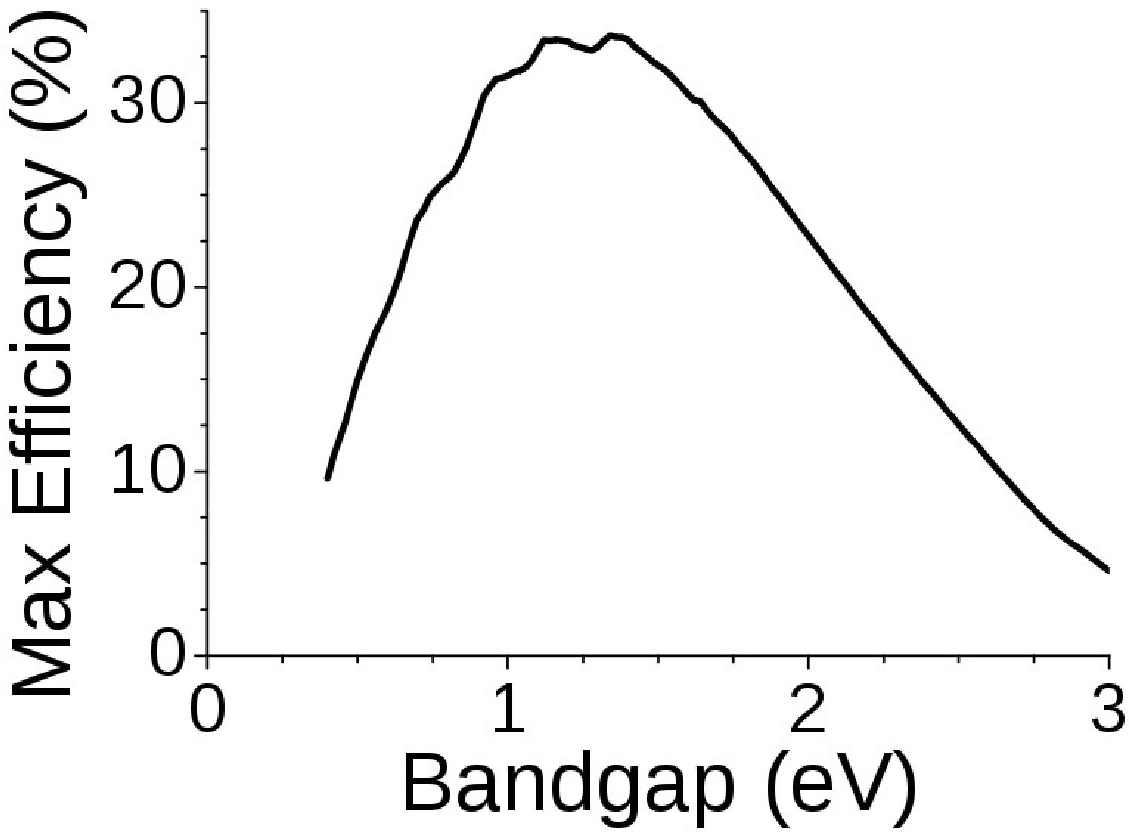






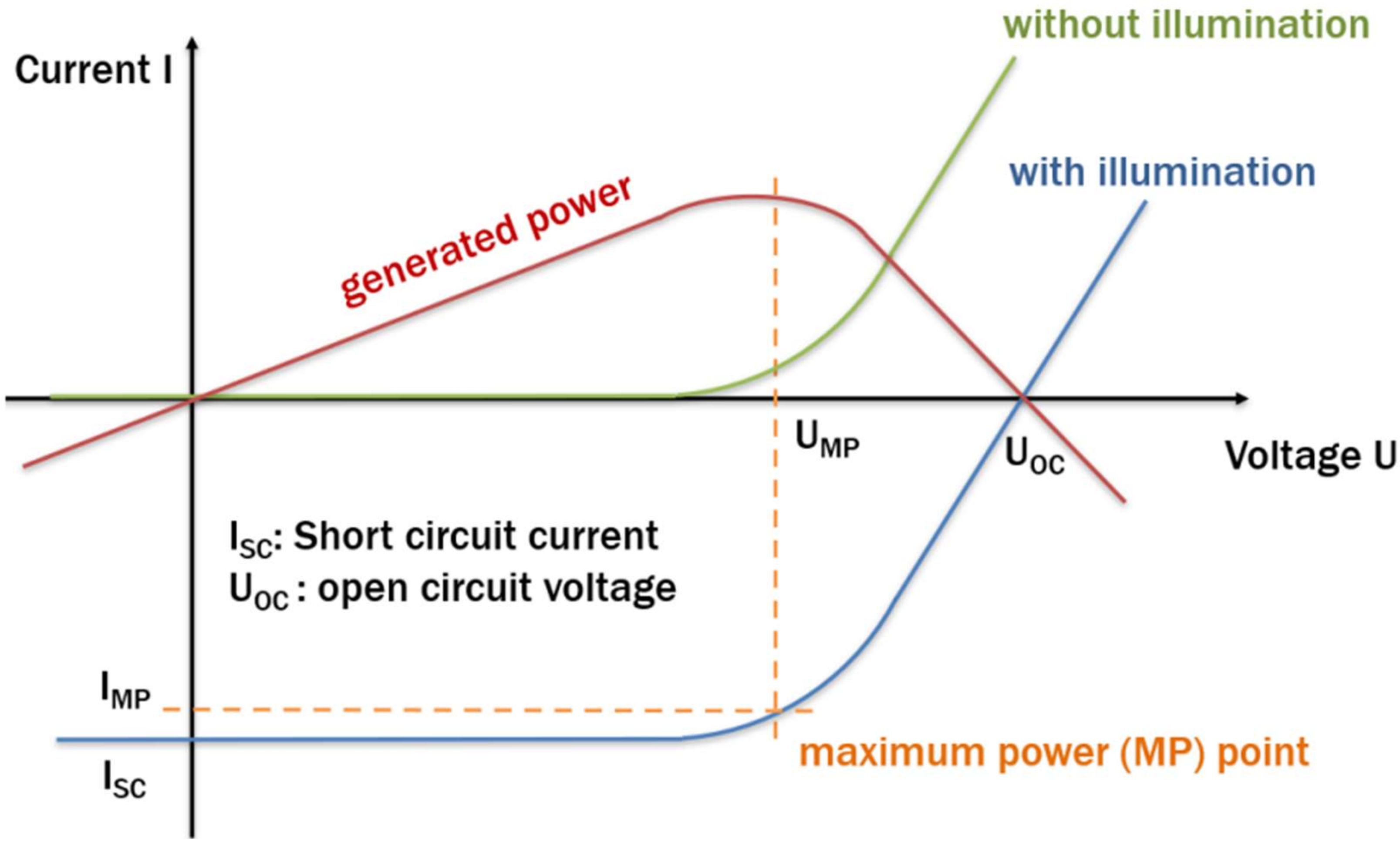
Wu, H.W. & Emadi, A & Graaf, G & Leijtens, Johan & Wolffenbuttel, R.F.. (2011). Design and Fabrication of an Albedo Insensitive Analog Sun Sensor. Procedia Engineering. 25. 527-530. 10.1016/j.proeng.2011.12.131.

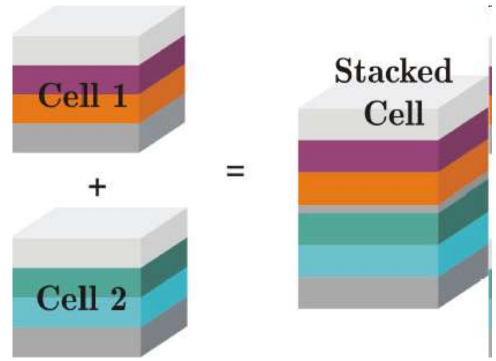
Shockley–Queisser limit

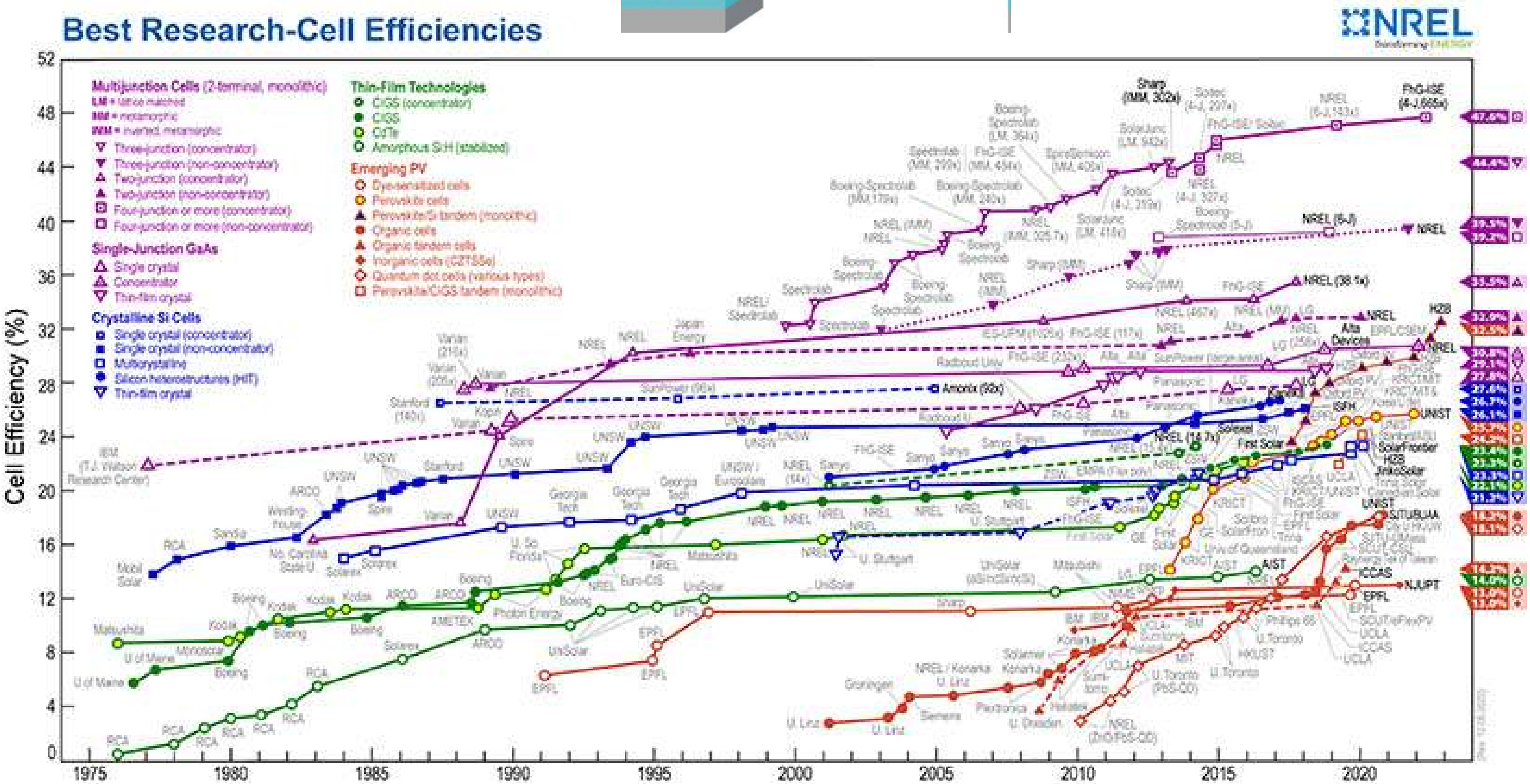


http://en.wikipedia.org/wiki/Shockley-Queisser_limit

Maximum power point



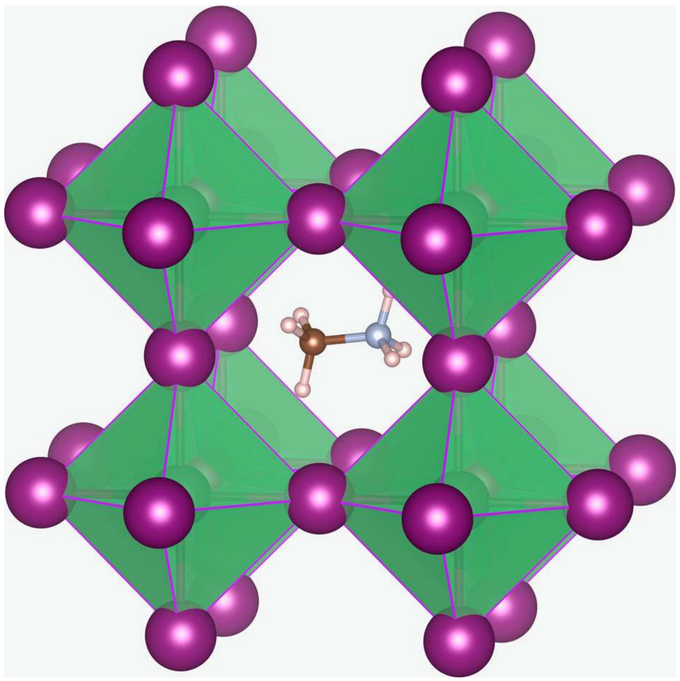




Biofuel efficiency ~ 1%

Perovskite solar cells

https://en.wikipedia.org/wiki/Perovskite_solar_cell#/media/File:CH3NH3PbI3_structure.png



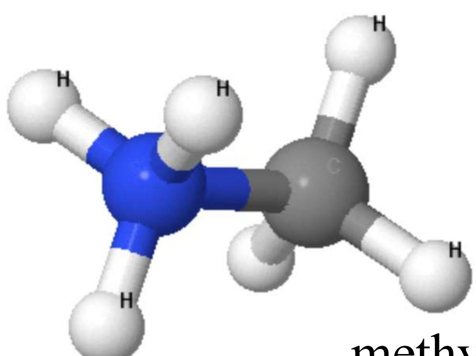
methylammonium lead trihalide ABX_3
$CH_3NH_3PbX_3$, where X is I, Br or Cl
Optical bandgap 1.5 - 2.3 eV

+ Cheaper to fabricate than Si solar cells.
(silicon cells require > 1000 C)

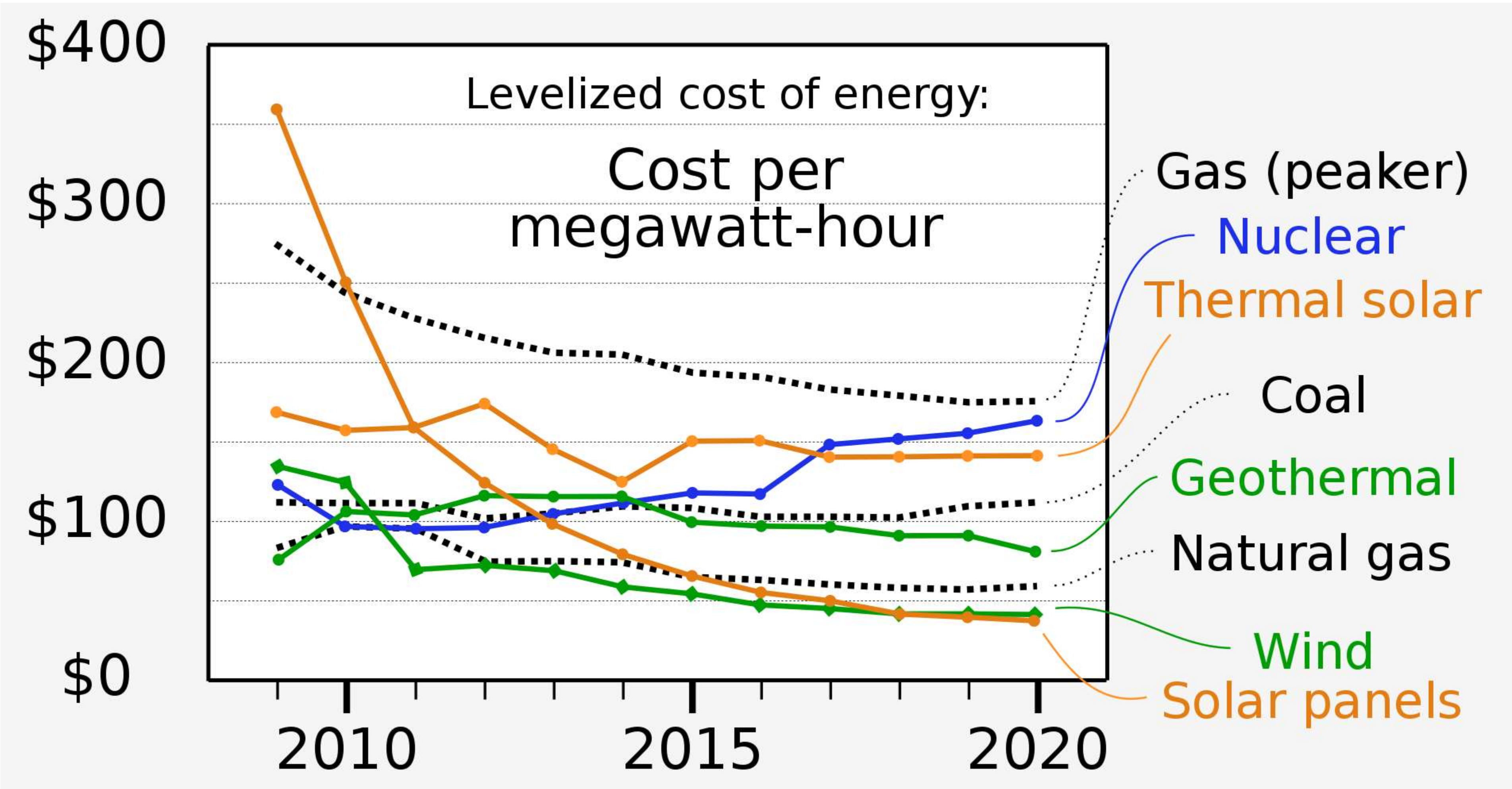
- Contains lead

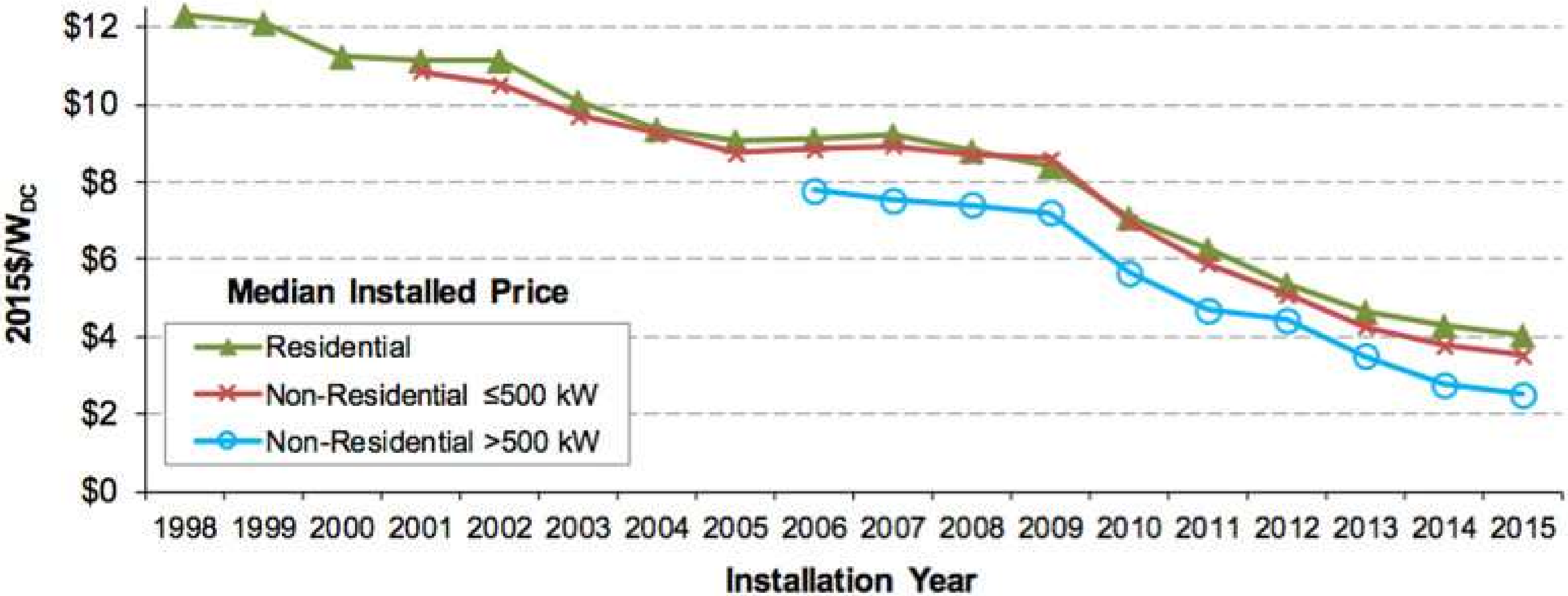
Also less efficient $CH_3NH_3SnI_3$ version

- Not stable



methylammonium

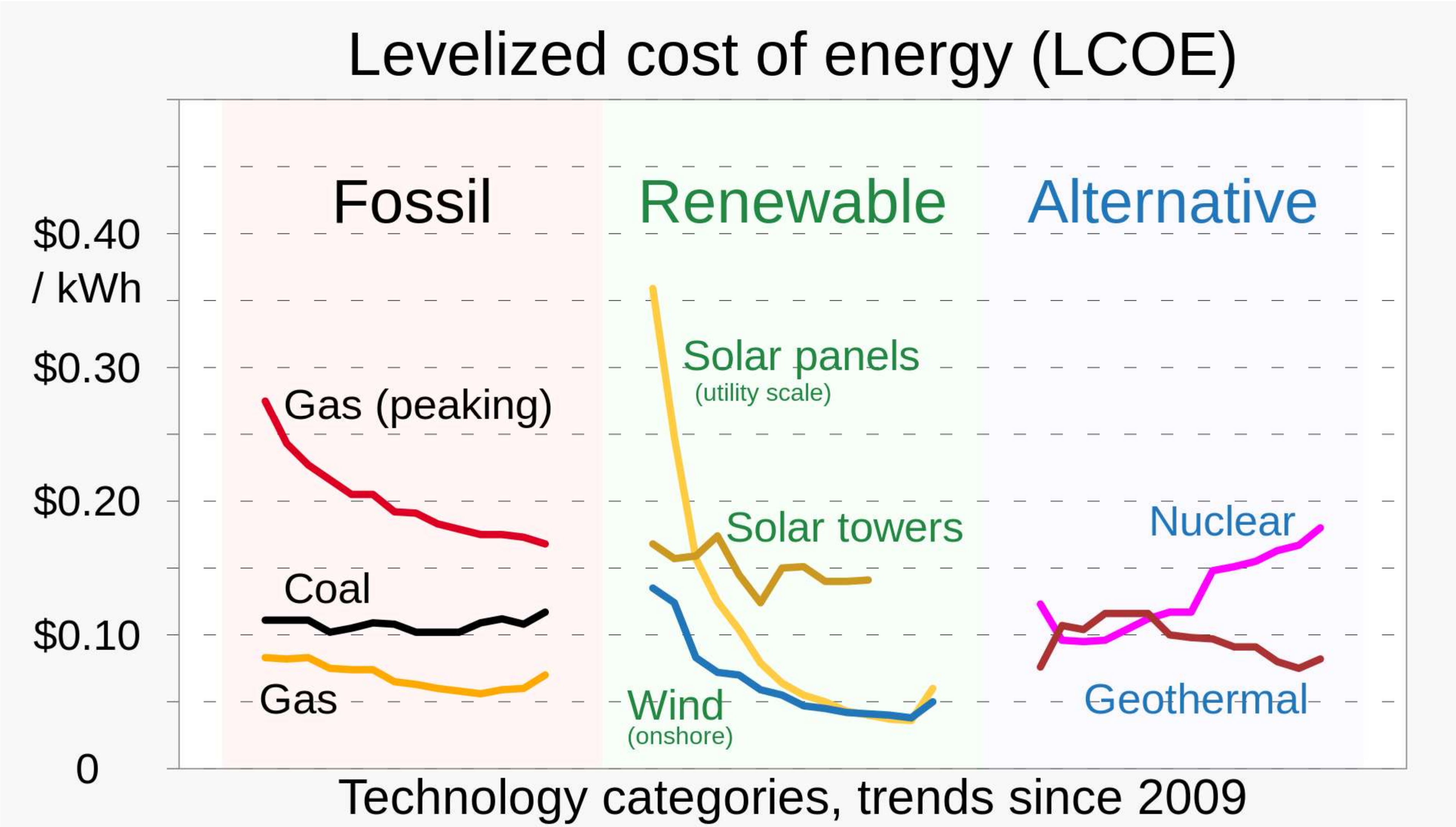

Levelized cost of energy:
Cost per megawatt-hour
$400
$300
$200
$100
$0
2010
2015
2020
Gas (peaker)
Nuclear
Thermal solar
Coal
Geothermal
Natural gas
Wind
Solar panels



Notes: See Table 1 for sample sizes by installation year. Median installed prices are shown only if 20 or more observations are available for a given year and customer segment.

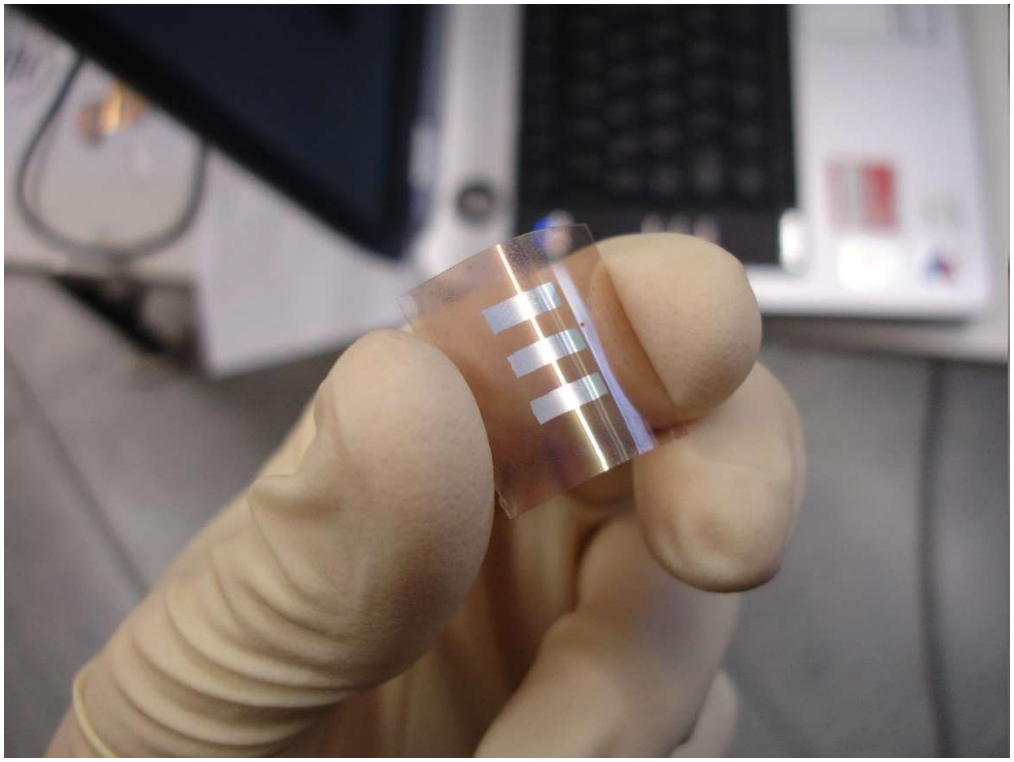
Figure 6. Median Installed Price Trends over Time

https://www.vox.com/2016/8/24/12620920/us-solar-power-costs-falling



https://en.wikipedia.org/wiki/Cost_of_electricity_by_source#/media/File:20201019_Levelized_Cost_of_Energy_(LCOE,_Lazard)_-_renewable_energy.svg

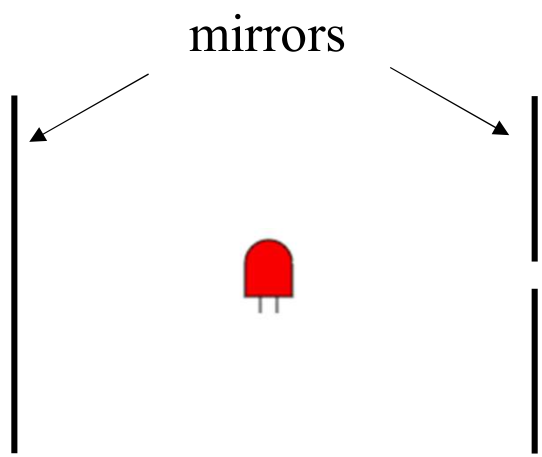
Printable solar cells



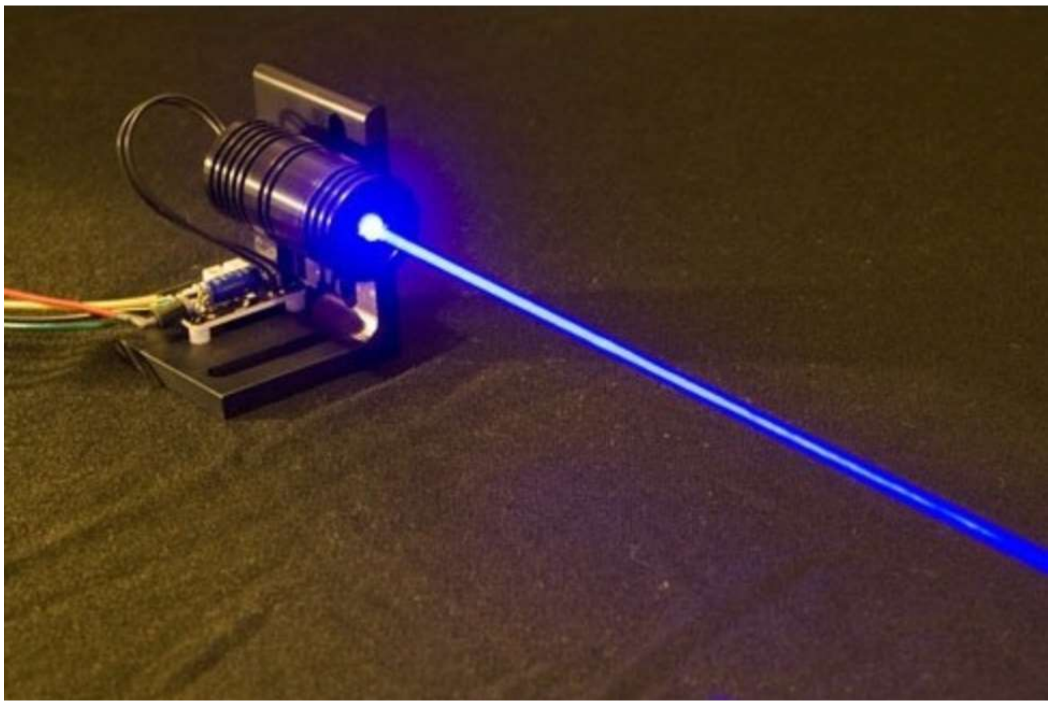
CD labor - TU Graz

Konarka

Laser Diodes

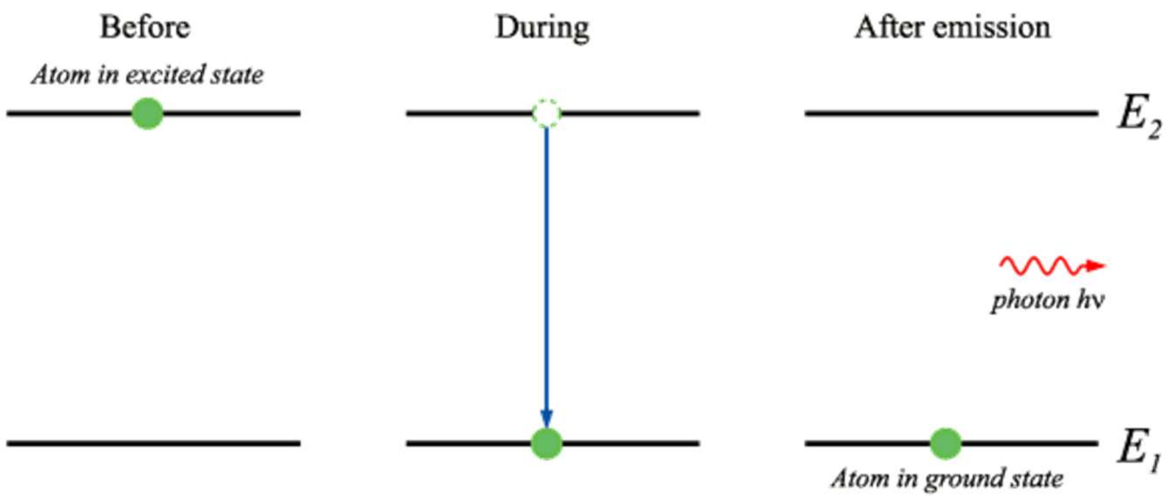


laser diodes



http://www.aliexpress.com/item/445nm-laser-diode/767127021.html

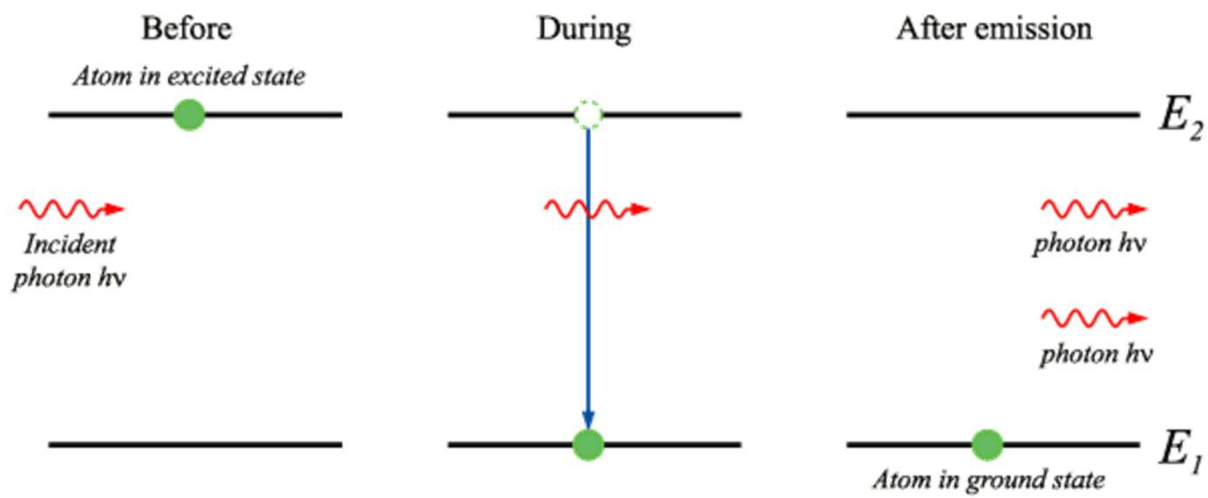
Spontaneous emission



$$h\nu = E_2 - E_1$$

Spontaneous emission dominates in fluorescent lighting and light emitting diodes. In a gas, the conservation of momentum is easily maintained. For a semiconductor, a direct bandgap material is necessary.

Stimulated emission



Stimulated emission is responsible for the coherent light of lasers.

$$W_{\text{stimulated}}(\omega) = W_{\text{spontaneous}}(\omega) \cdot n_{ph}(\omega)$$

laser diodes

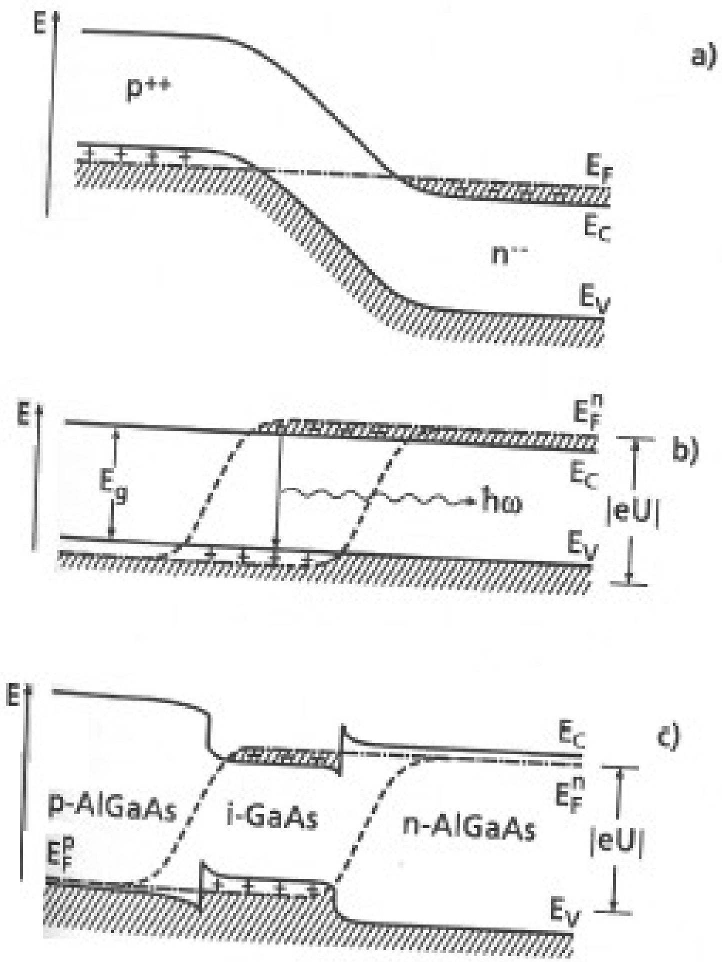
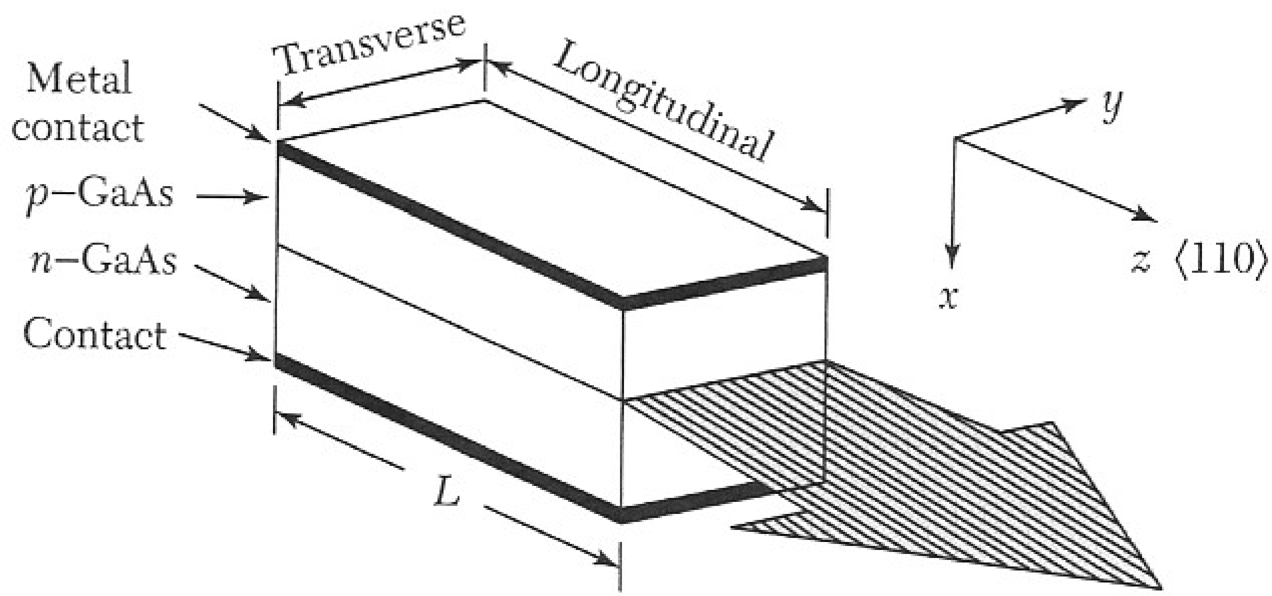


Fig. 12.37. Electronic band schemes $E(x)$ of *pn*-semiconductor laser structures along a direction x perpendicular to the layer structure: **(a)** Degenerately doped $p^{++}n^{--}$ junction without external bias (thermal equilibrium); **(b)** same $p^{++}n^{--}$ junction with maximum bias U in forward direction; **(c)** double-heterostructure pin junction of *p*-AlGaAs/*i*-GaAs/*n*-AlGaAs with maximum bias U in forward direction. E_F^n, E_F^p are the quasi-Fermi levels in the *n*- and *p*-region, respectively; E_C and E_V are conduction and valence band edges

Ibach & Lueth, *Solid-State Physics*

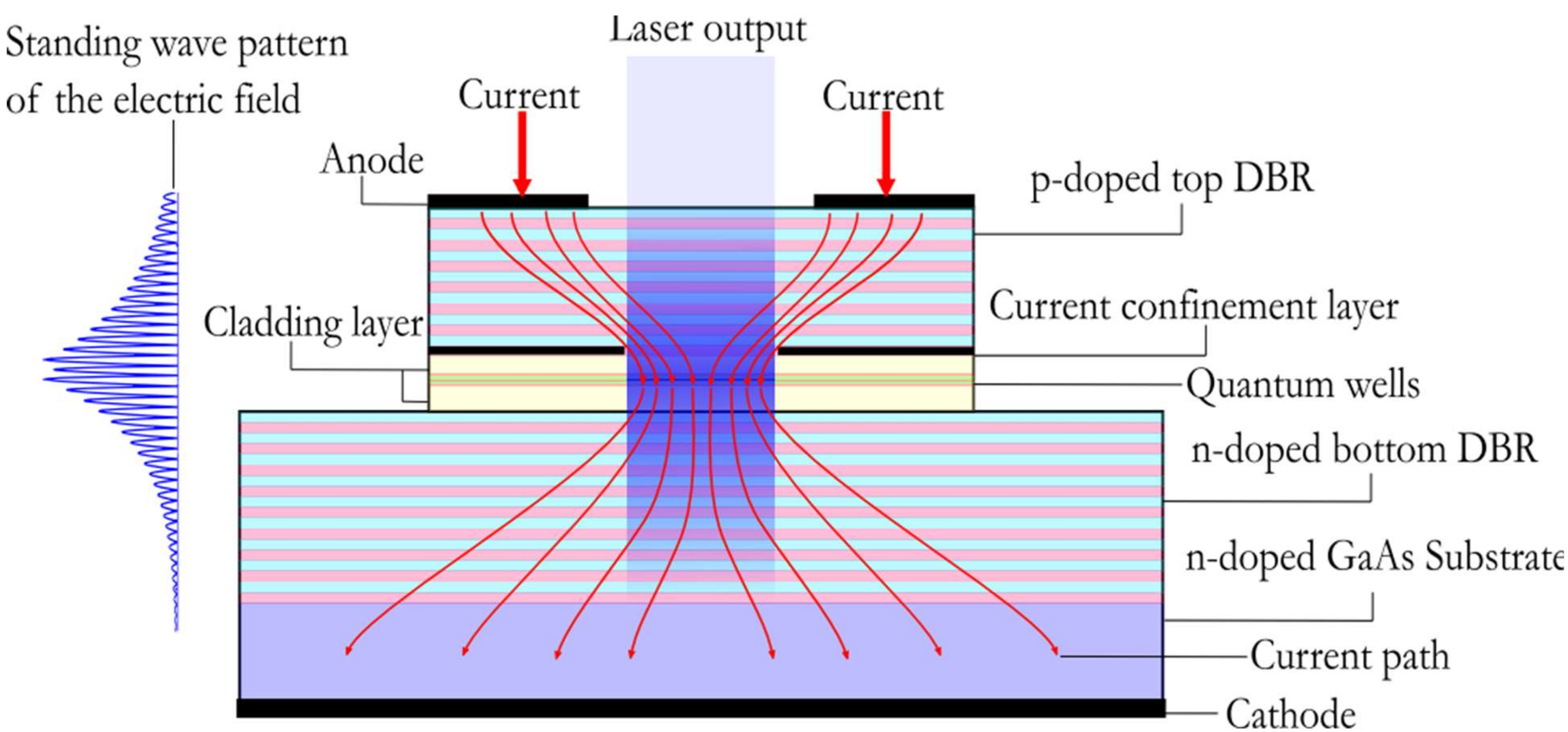
Laser diode

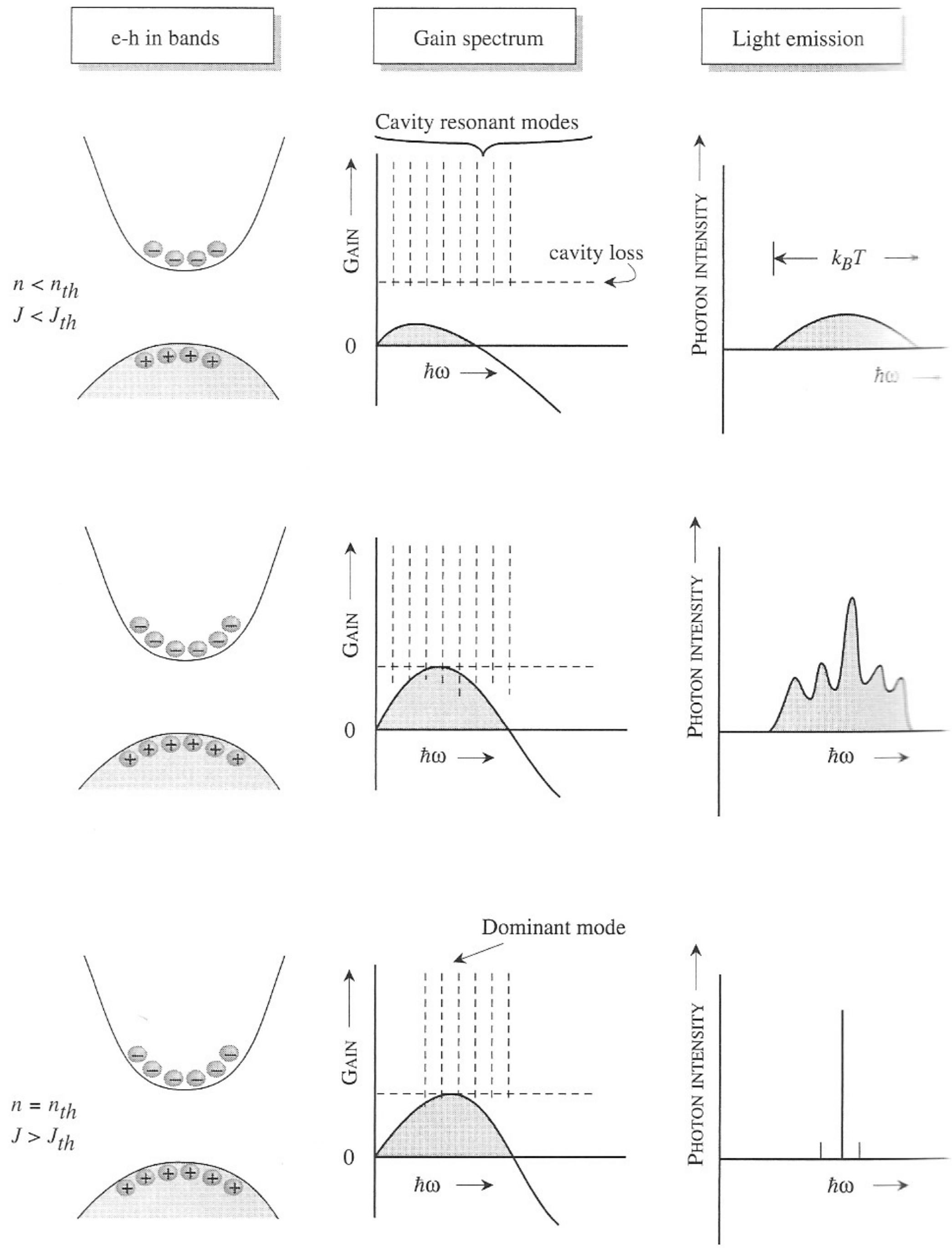


(a)

The faces of the crystal are cleaved to make mirrors.

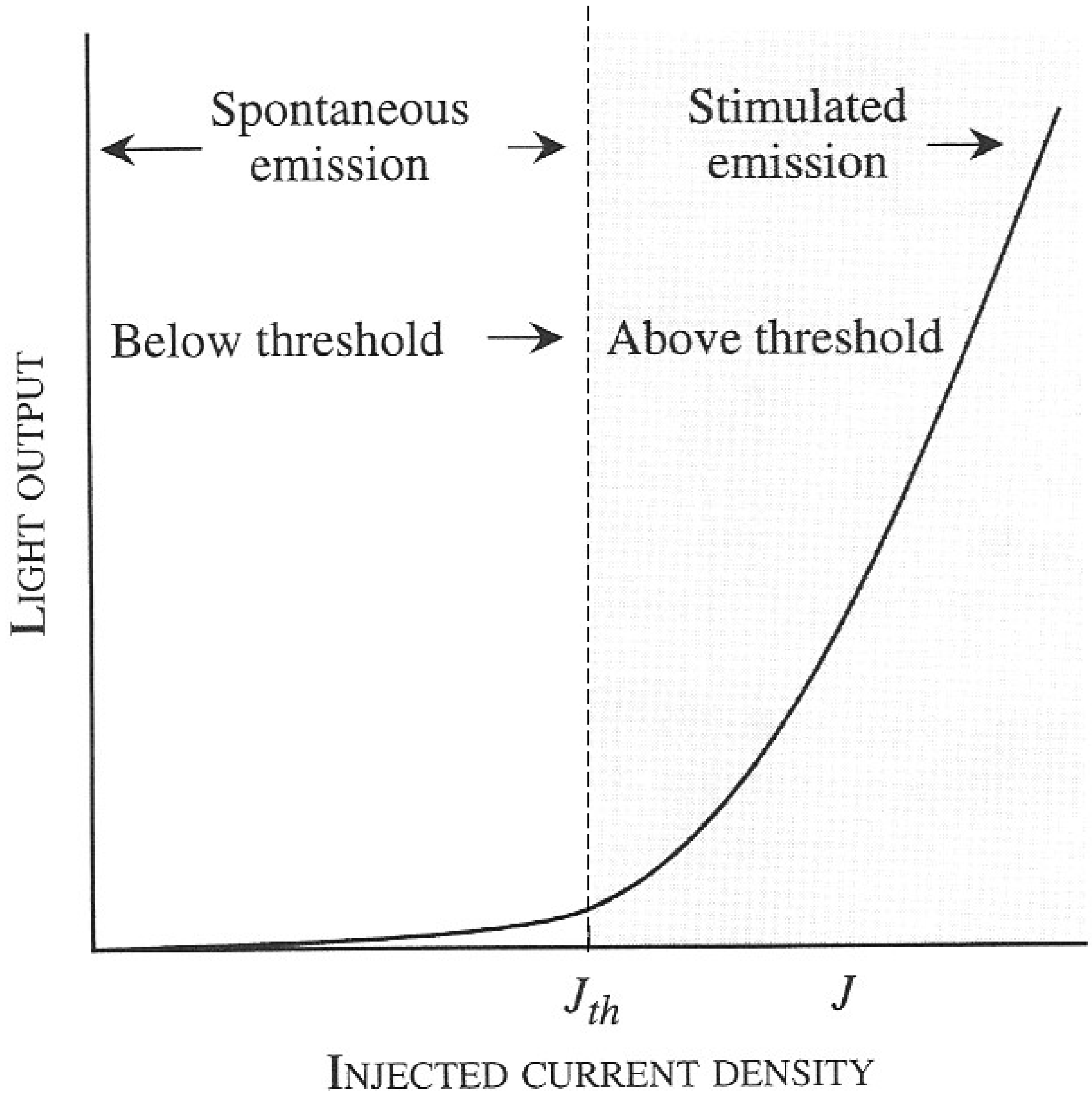
Vertical-cavity surface-emitting laser (VCSEL)



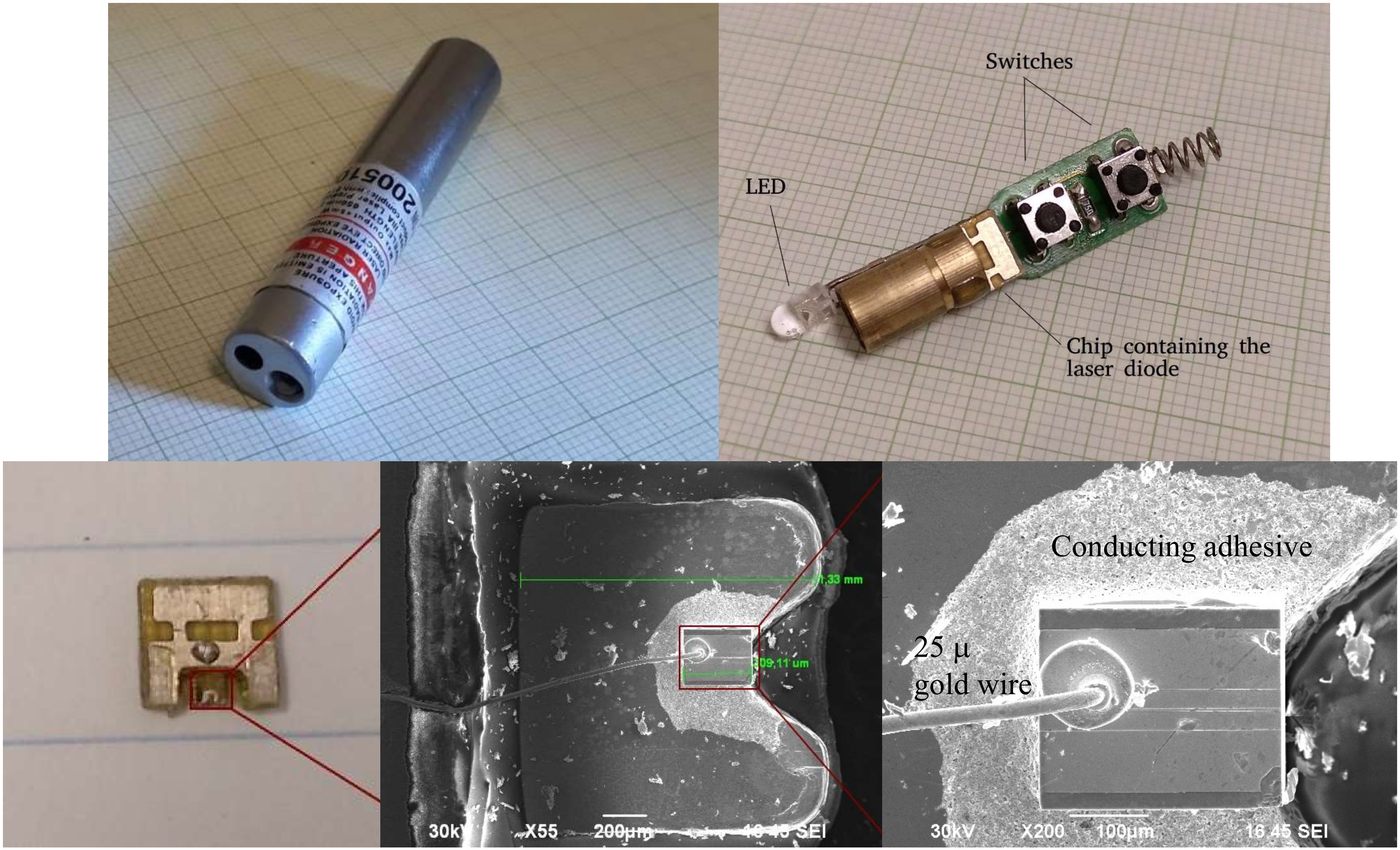


e-h in bands
Gain spectrum
Light emission
Cavity resonant modes
cavity loss
GAIN
0
ħω
PHOTON INTENSITY
k_BT
$n < n_{th}$
$J < J_{th}$
Dominant mode
$n = n_{th}$
$J > J_{th}$

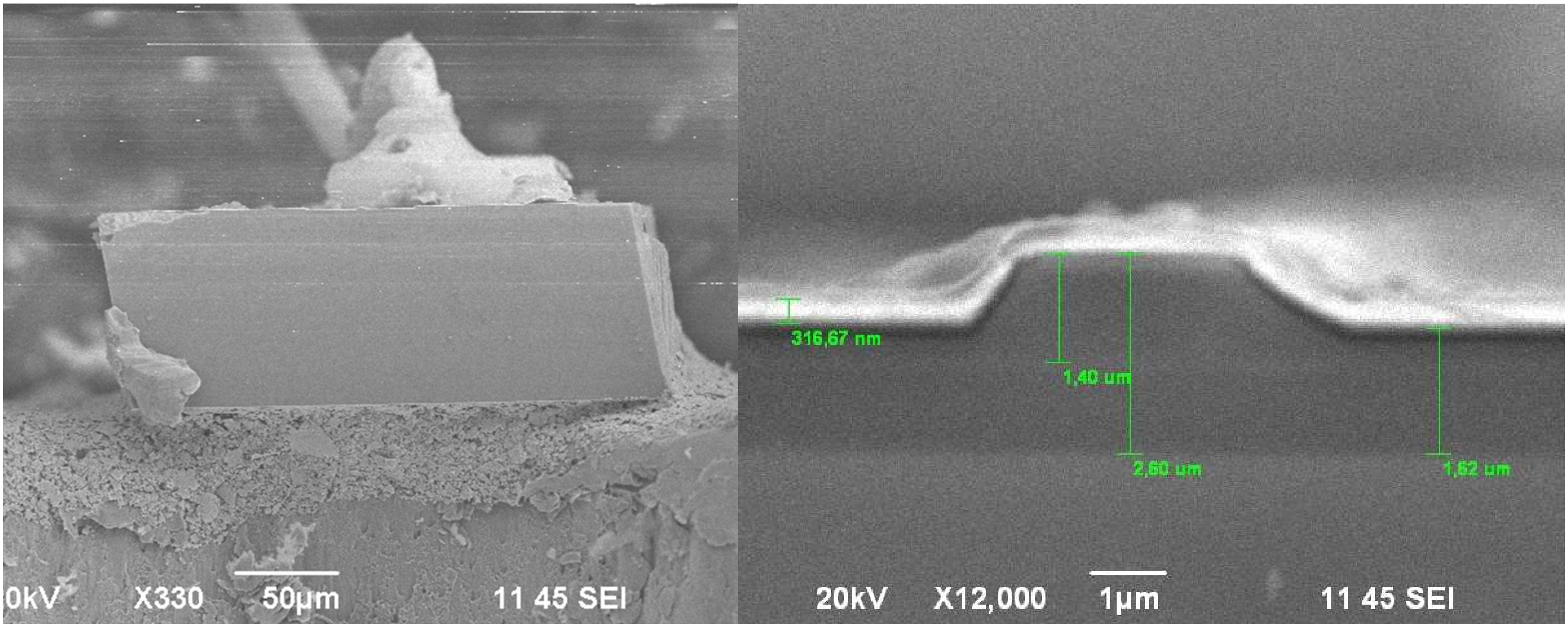
Stimulated emission



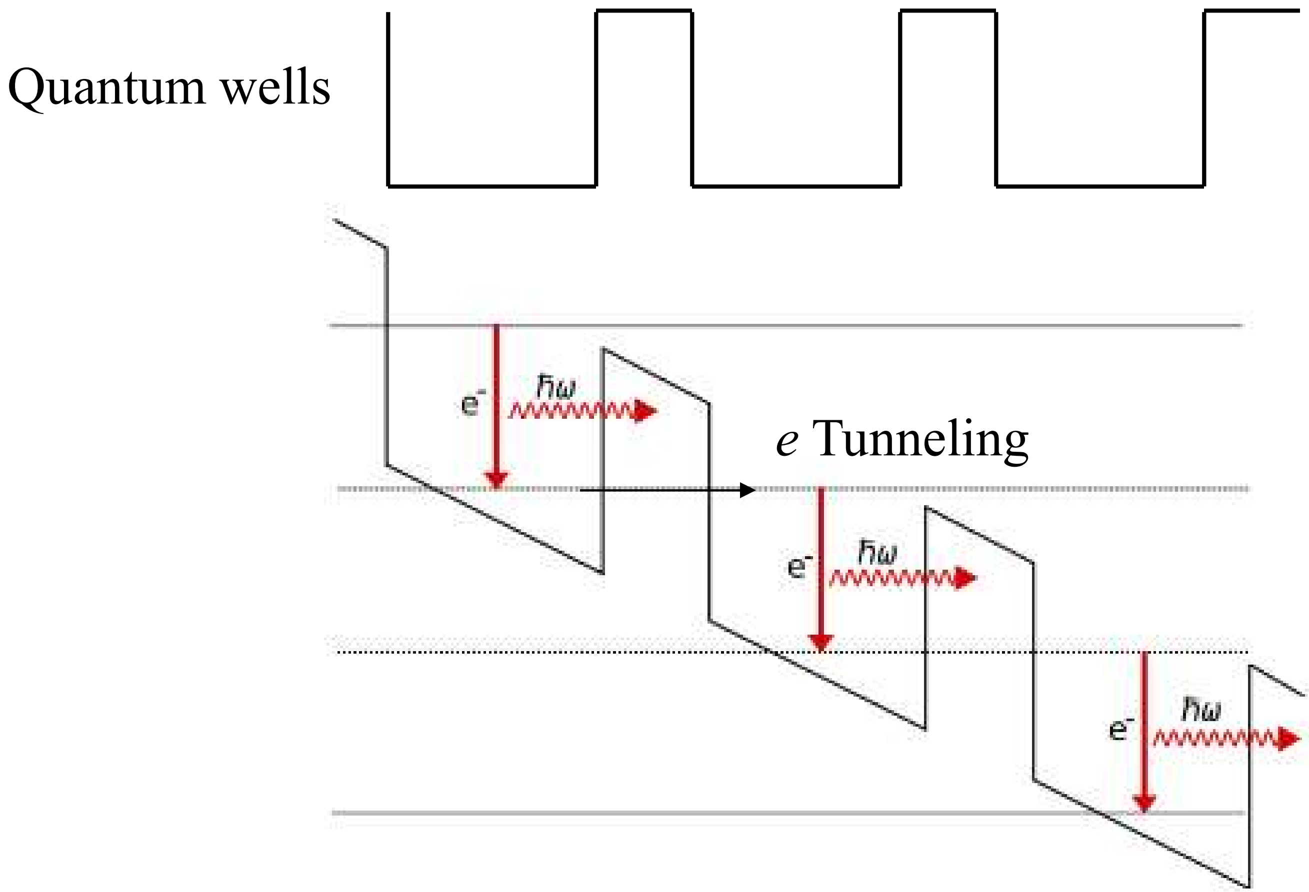
Laser pointer



Laser pointer



Quantum cascade lasers

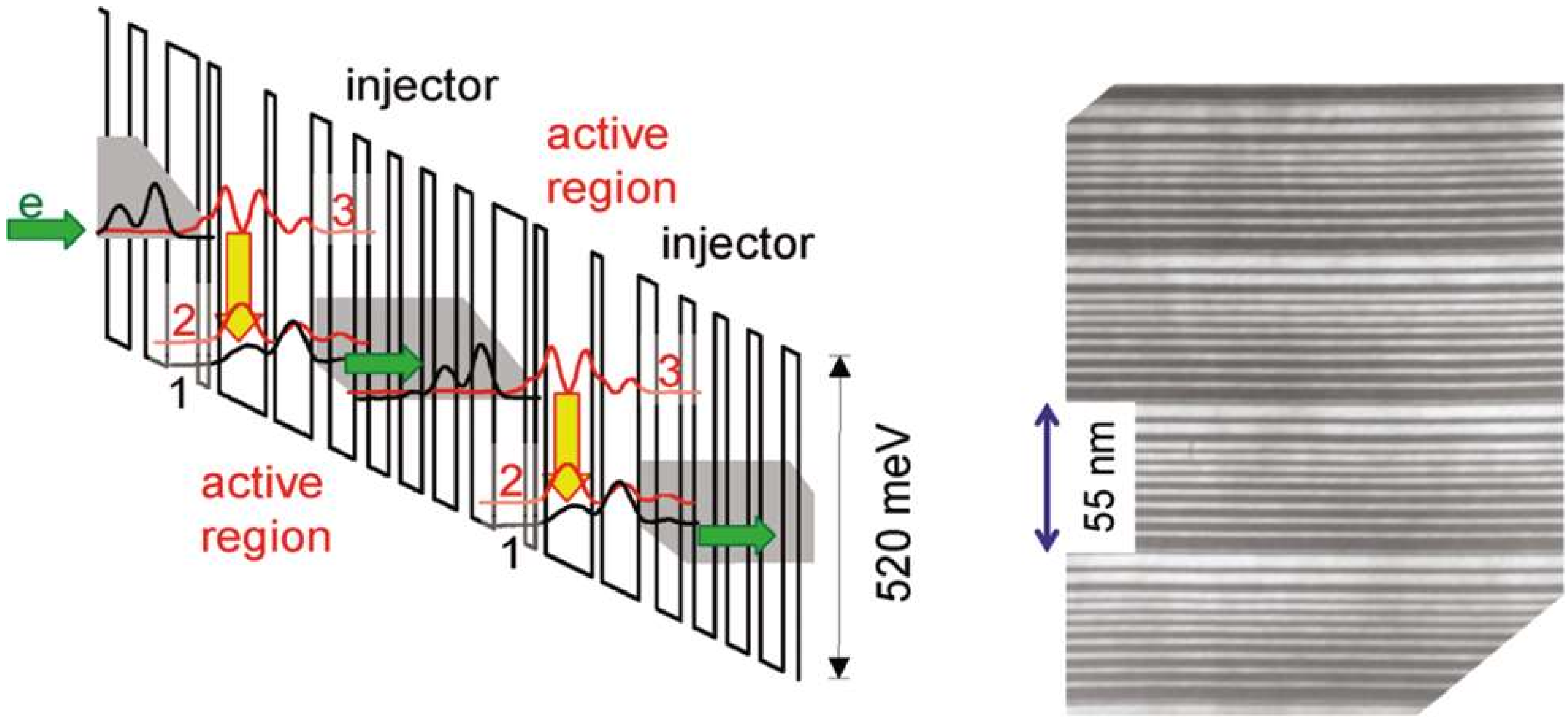


Energy levels depend on the width of the wells so lasers can be made at many frequencies (mid to far infrared 2.75 - 250 μm).

Many colors can be made with one materials system.

Window in atmosphere at 5 μm used for point-to-point communications.

Quantum cascade lasers



(a) (b)

http://opticalengineering.spiedigitallibrary.org/article.aspx?articleid=1096486