12

Optoelectronics

January 2026

Exam

January 26, 18:00 – 19:00 P1

A4 of handwritten notes

Calculator

Optoelectronics

- light emitting diode
- laser diode
- solar cell
- photo detectors

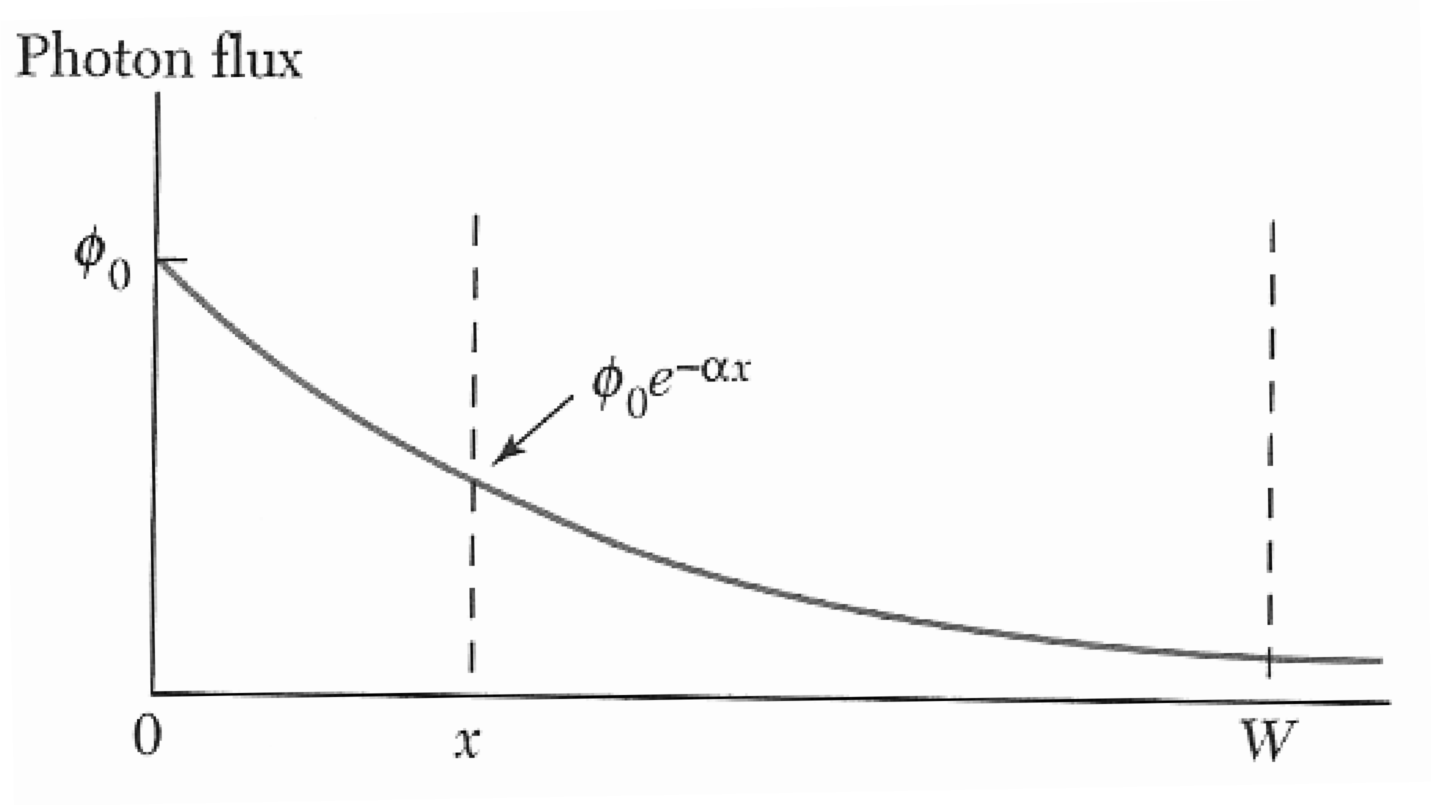
- communications

- displays
- lighting
- LiFi

- printing
- bar-code readers
- laser surgery
- measurement
- memory (DVD)
- spectroscopy

- guidance
- solar energy

Absorption



Photon flux

number of photons per second per unit area

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

α .. absorption coefficient

depends on material

depends on photon energy (wavelength)

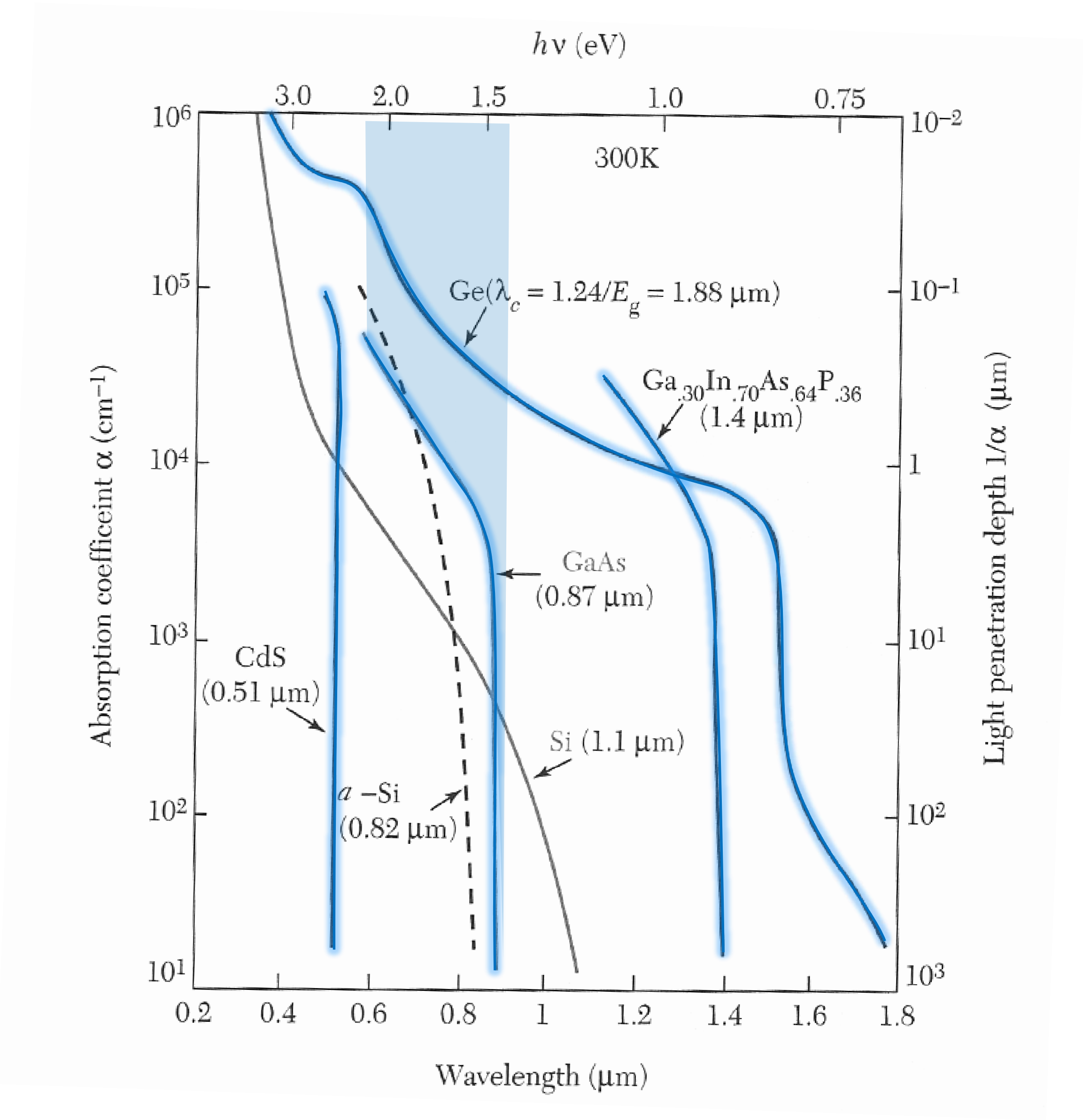
Absorption

Sharp absorption edge for
direct bandgap materials

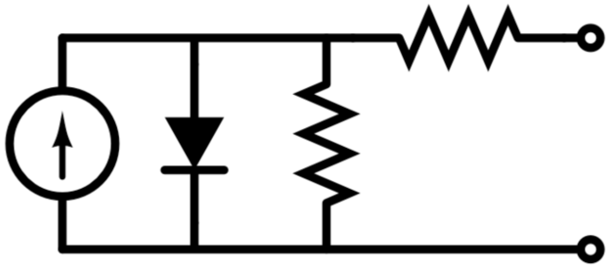
$$\alpha \approx 3.5 \times 10^6 \left(\frac{m_r^*}{m_0}\right)^{\frac{3}{2}} \frac{\sqrt{\hbar\omega - E_g}}{\hbar\omega} \quad \mathrm{cm}^{-1}$$

indirect bandgap

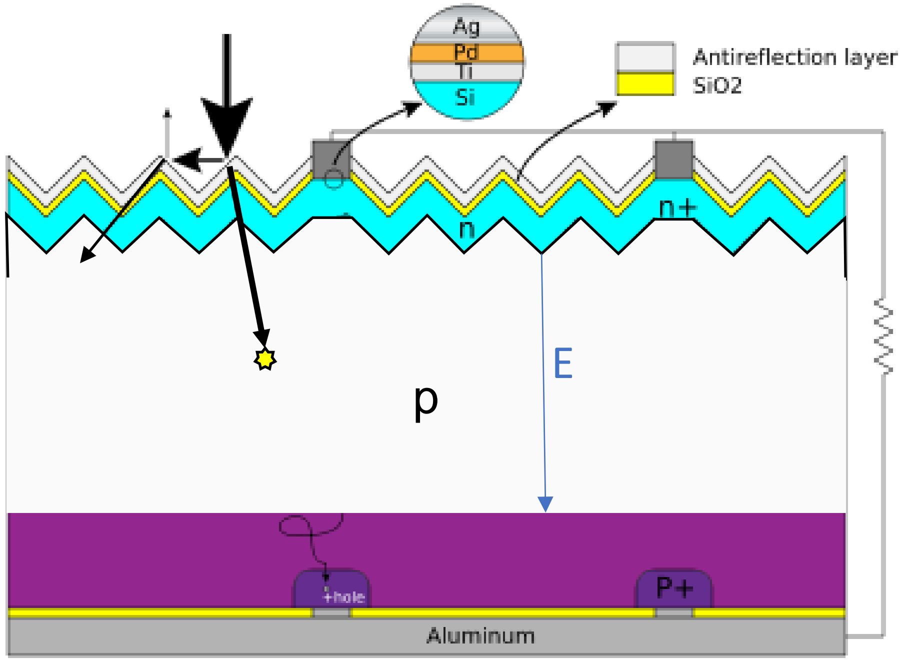
$$\alpha \propto \frac{(h\nu - E_g + E_p)^2}{exp(\frac{E_p}{k_B T}) - 1} + \frac{(h\nu - E_g - E_p)^2}{1 - exp(-\frac{E_p}{k_B T})}$$

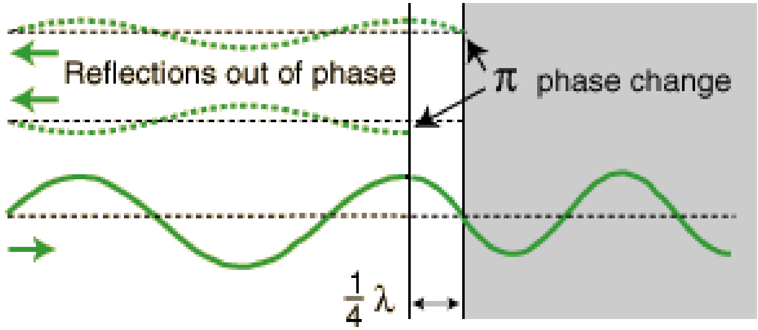


Solar cell



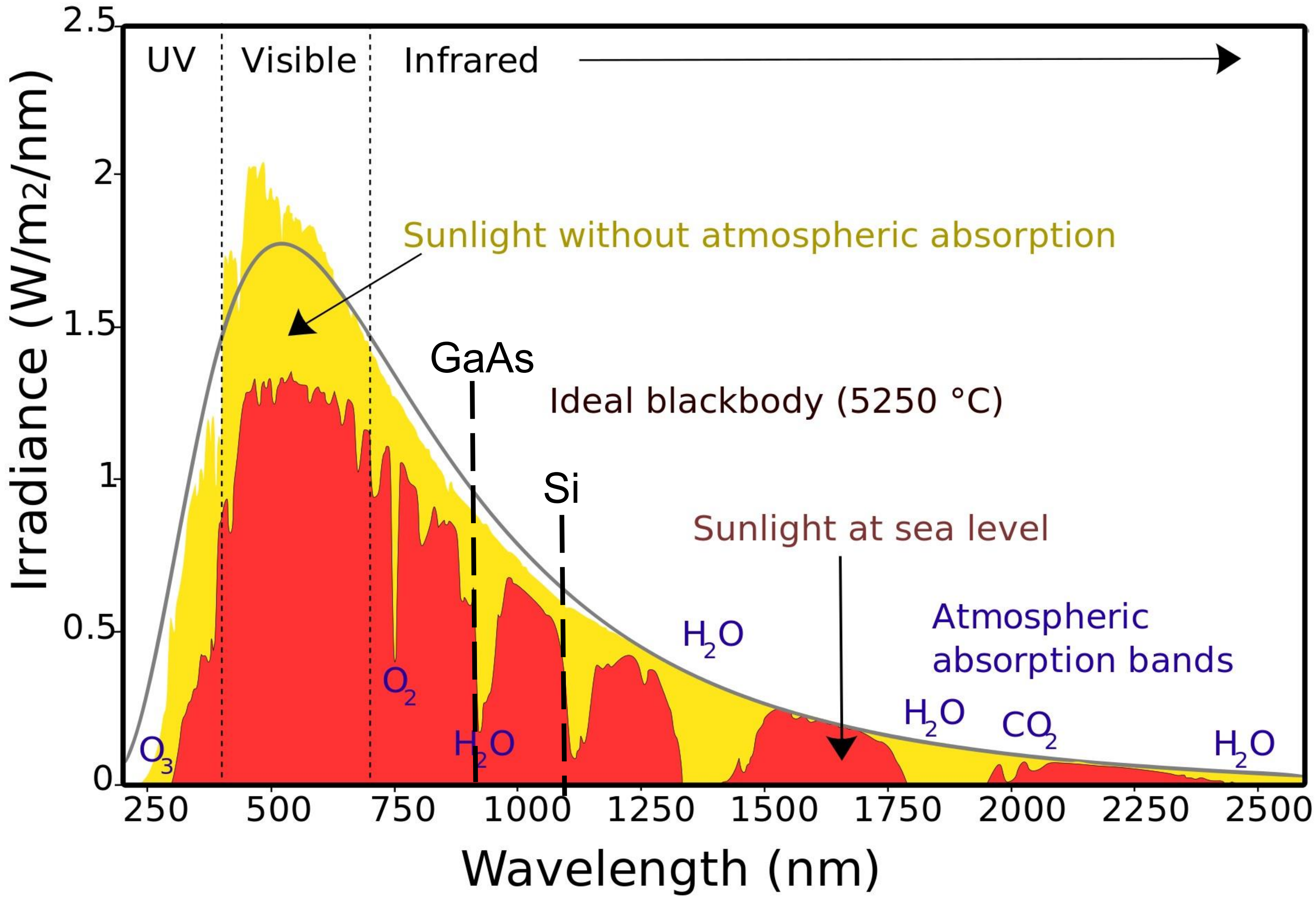
Equivalent circuit





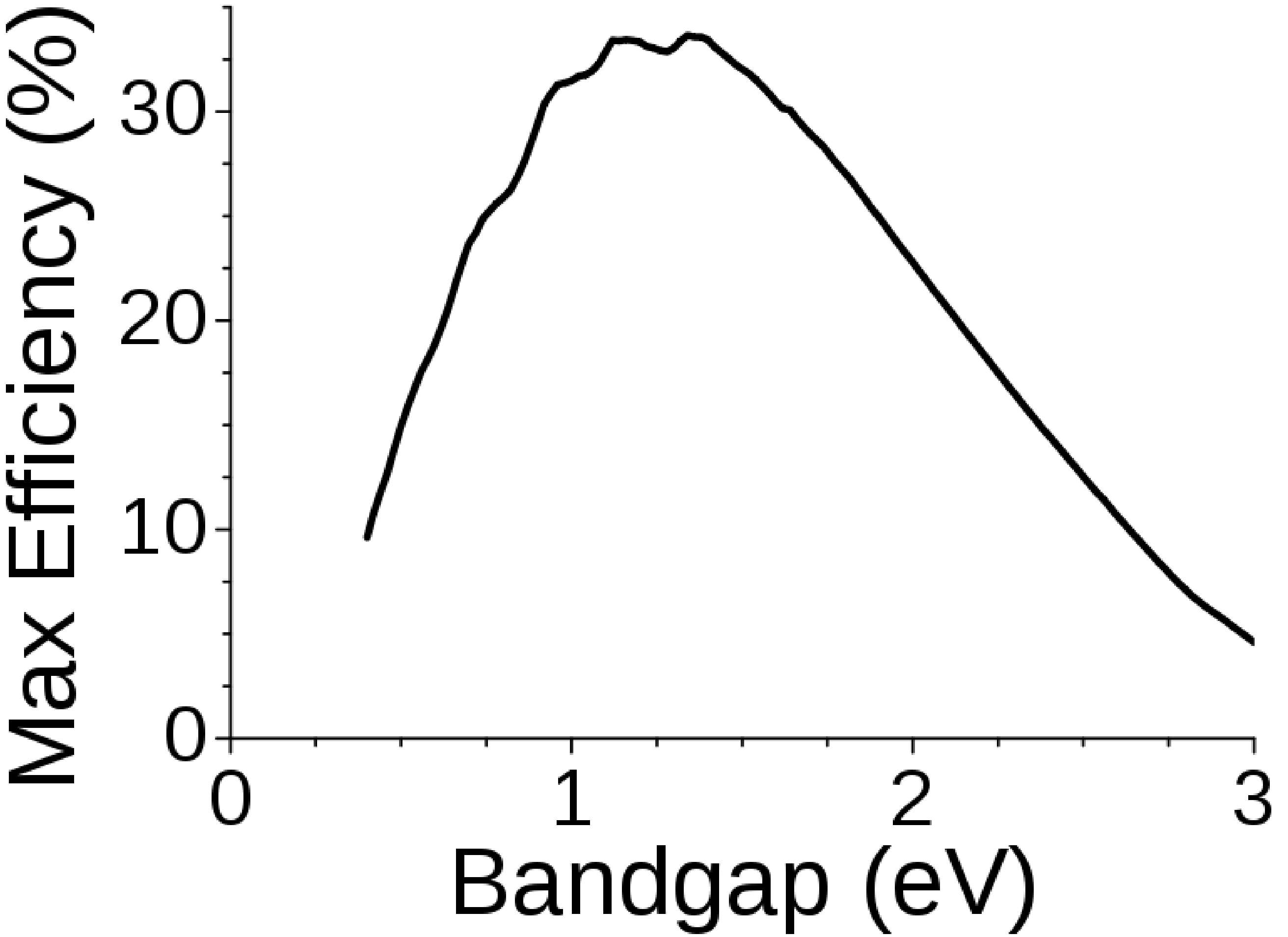
http://hyperphysics.phy-astr.gsu.edu/hbase/phyopt/antiref.html

Spectrum of Solar Radiation (Earth)



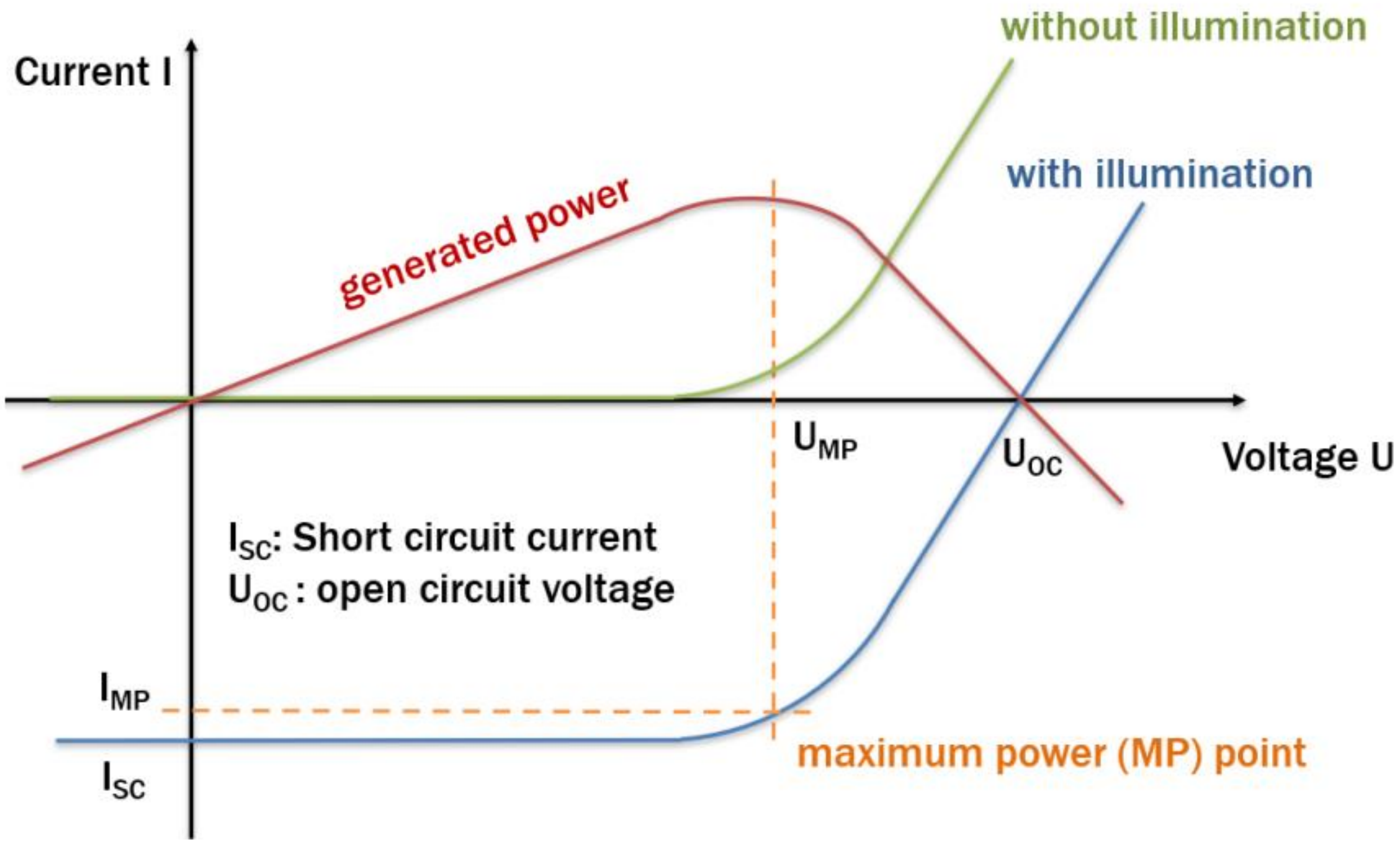
Wu, H.W. & Emadi, A & Graaf, G & Leijtens, Johan & Wolffenbuttel, R.F.. (2011). Design and Fabrication of an Albedo Insensitive Analog Sun Sensor. Procedia Engineering. 25. 527-530. 10.1016/j.proeng.2011.12.131.

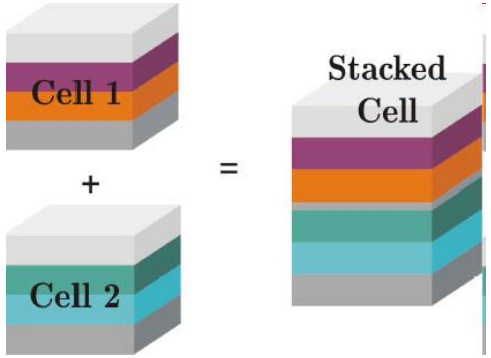
Shockley Queisser limit

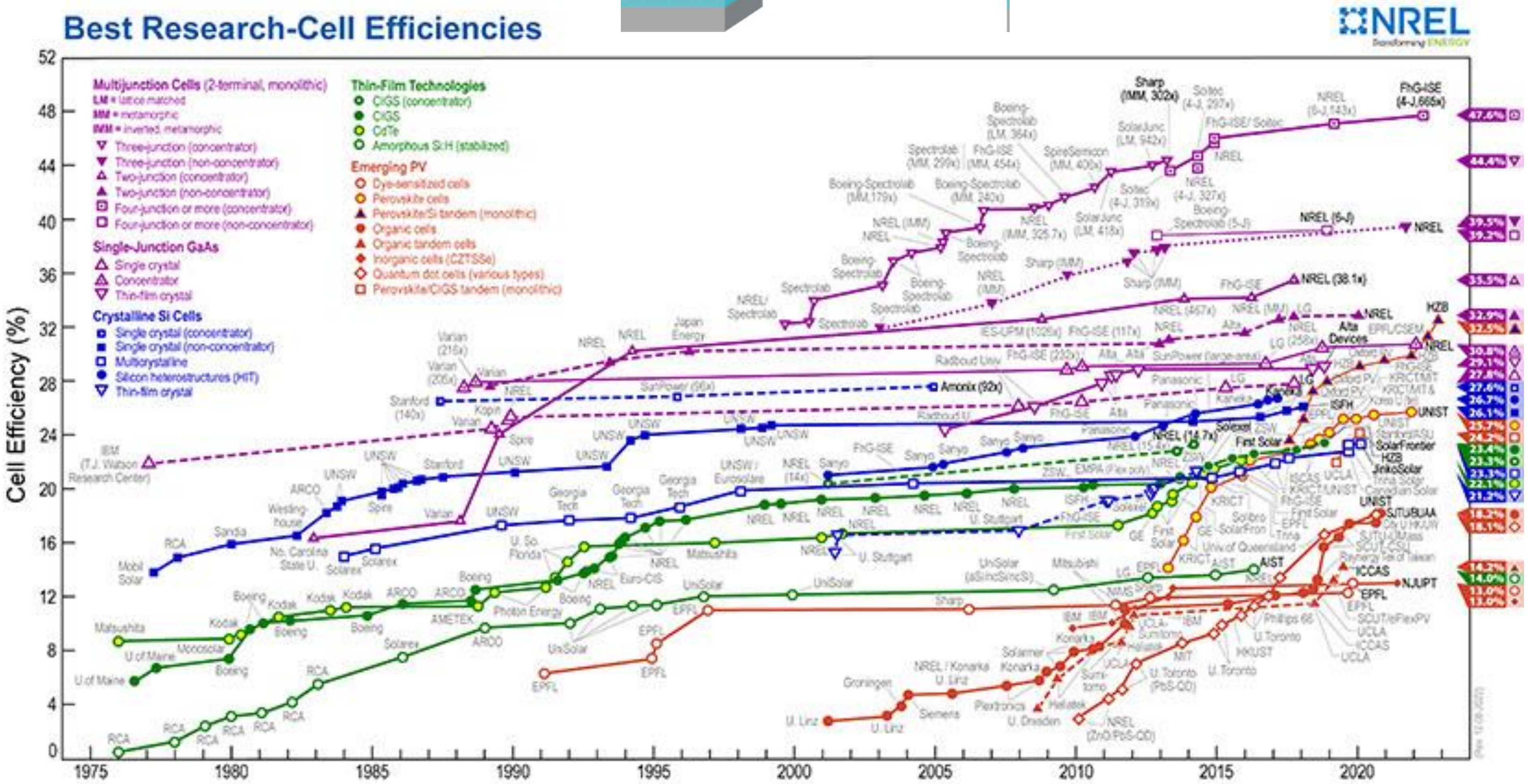


http://en.wikipedia.org/wiki/Shockley-Queisser_limit

Maximum power point





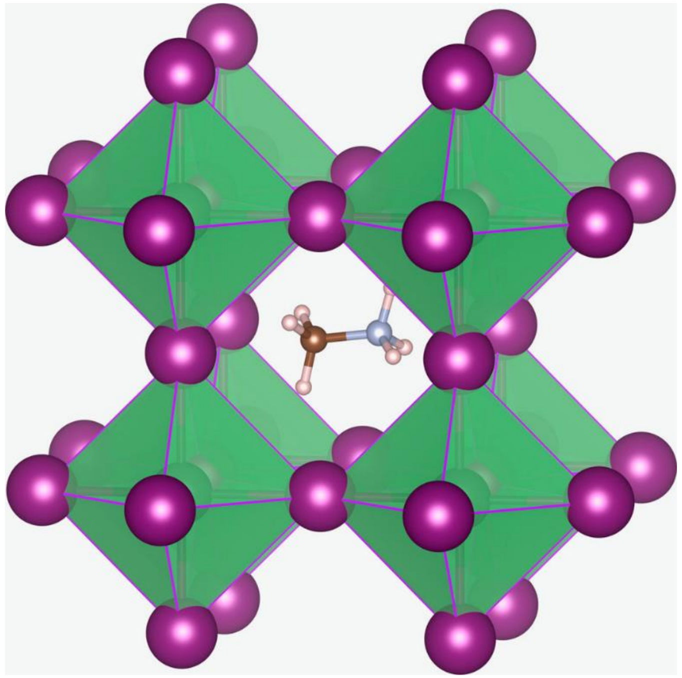


Biofuel efficiency ~ 1%

https://www.nrel.gov/pv/interactive-cell-efficiency

Perovskite solar cells

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



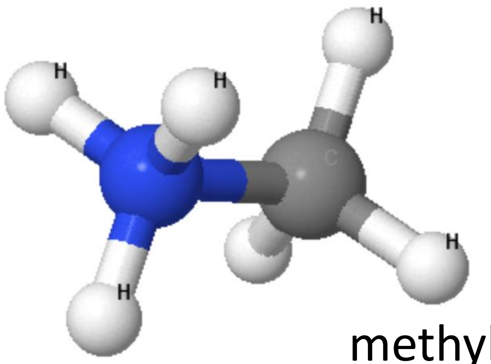
methylammonium lead trihalide ABX_3
$CH_3NH_3PbX_3$, where X is I, Br or Cl
Optical bandgap 1.5 - 2.3 eV

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

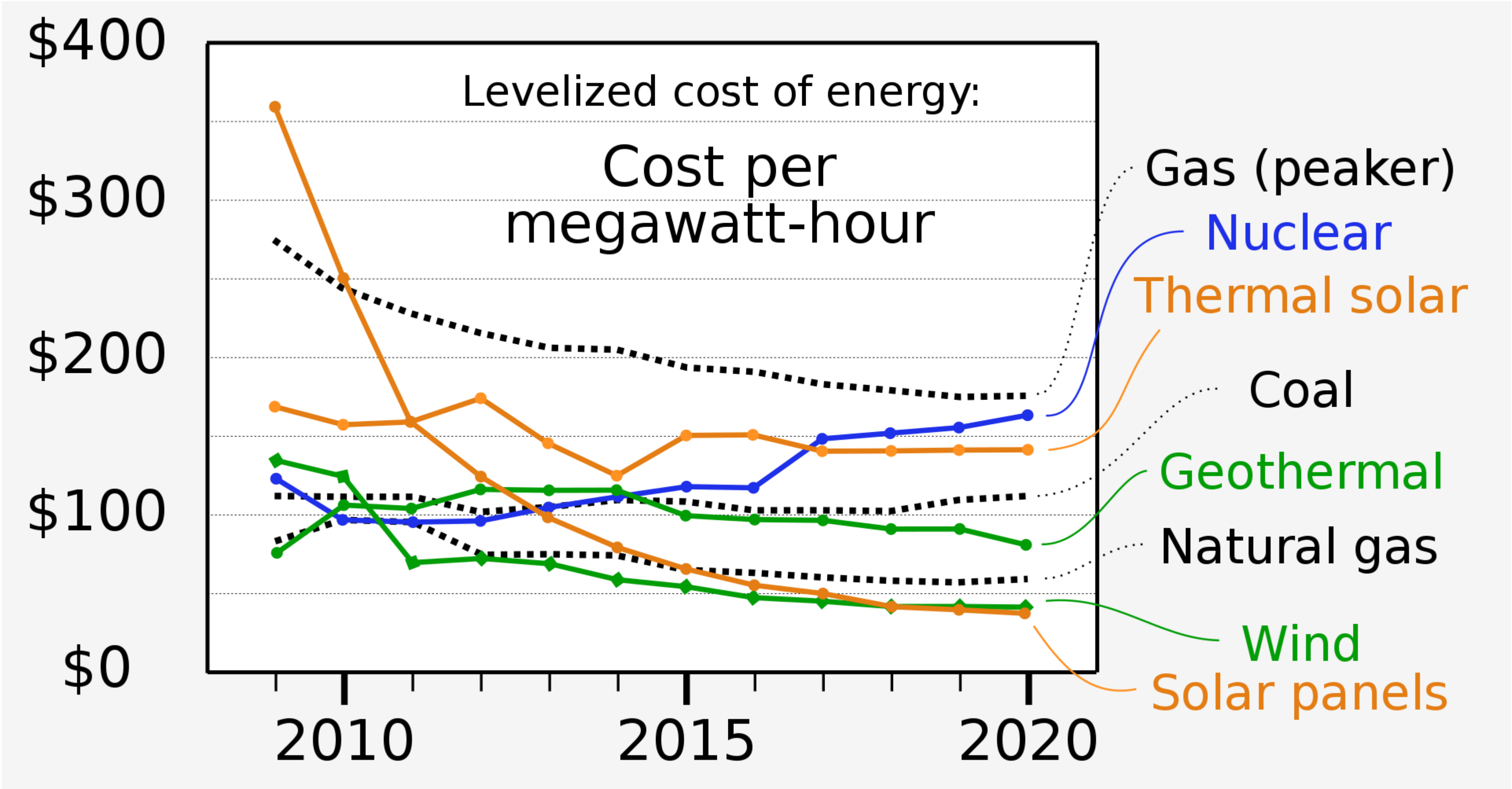
- Contains lead

Also less efficient $CH_3NH_3SnI_3$ version

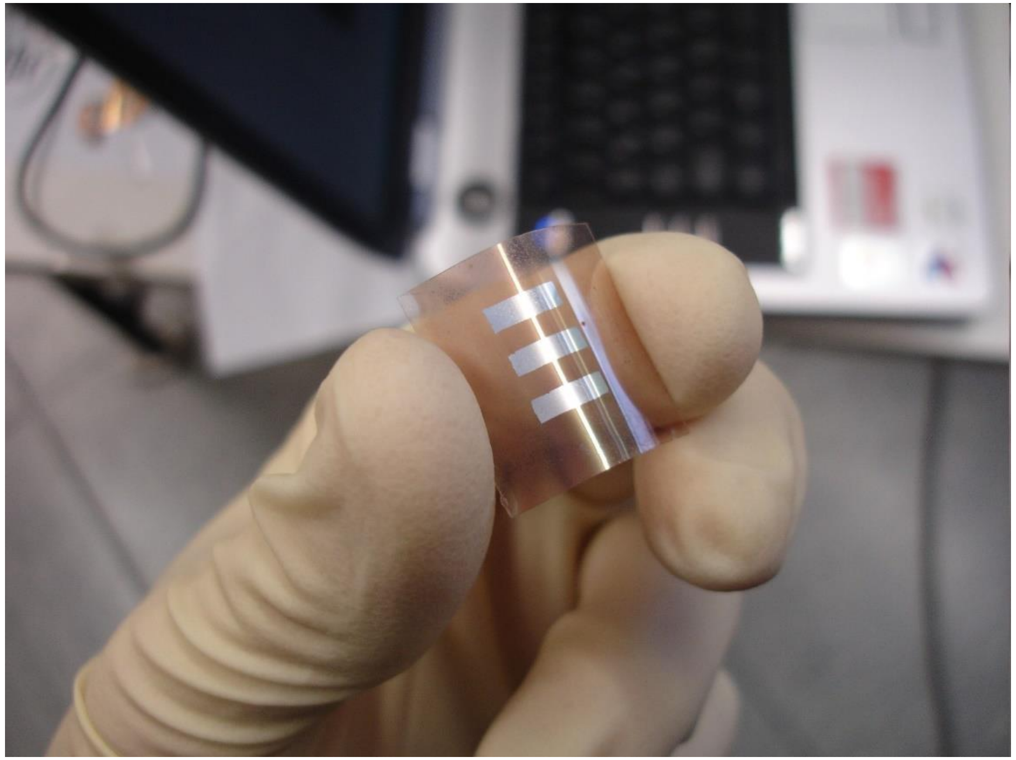
- Not stable



methylammonium

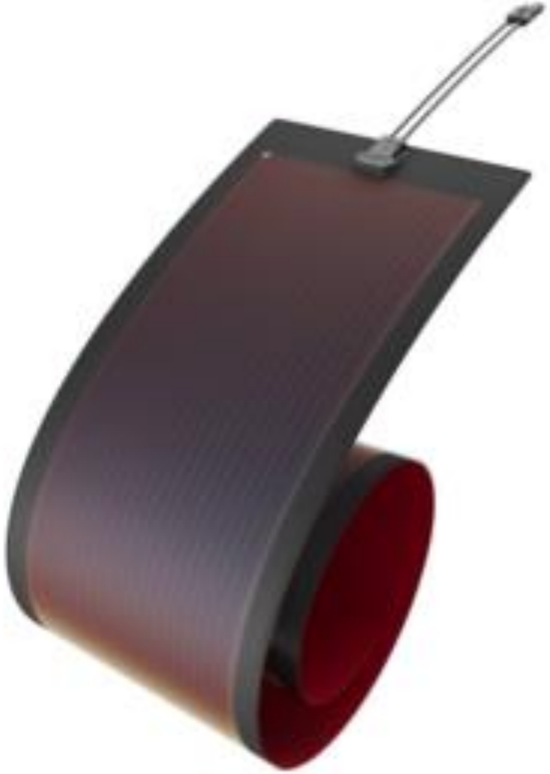

Levelized cost of energy:
Cost per
megawatt-hour
$400
$300
$200
$100
$0
2010
2015
2020
Gas (peaker)
Nuclear
Thermal solar
Coal
Geothermal
Natural gas
Wind
Solar panels

Organic solar cells



CD labor - TU Graz

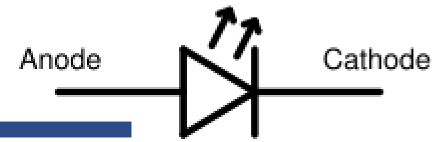
printed

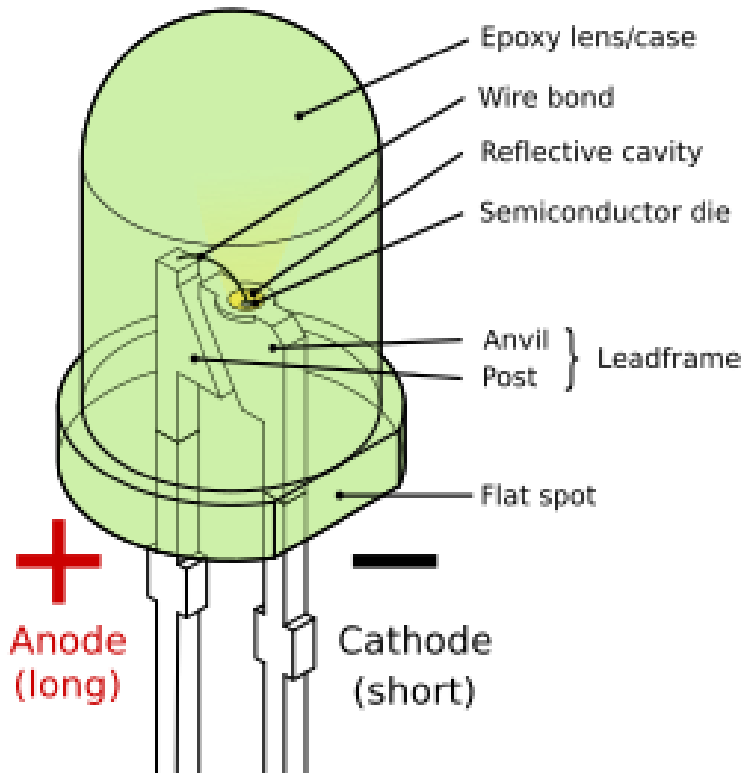


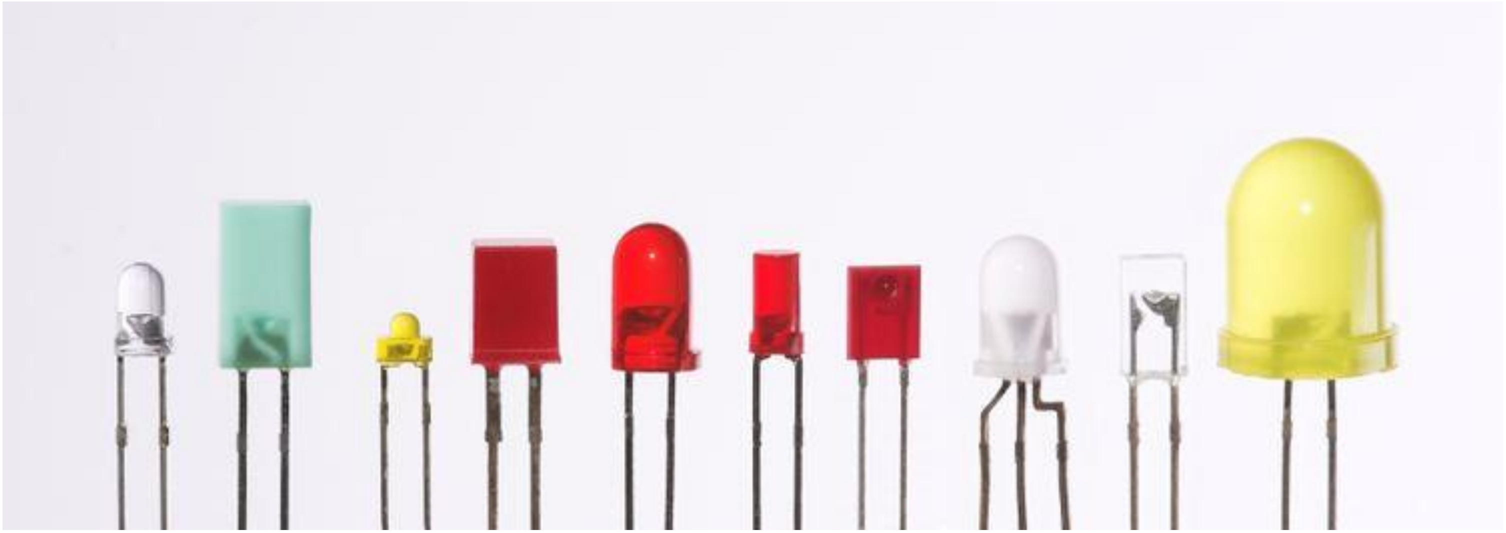
Heliatek

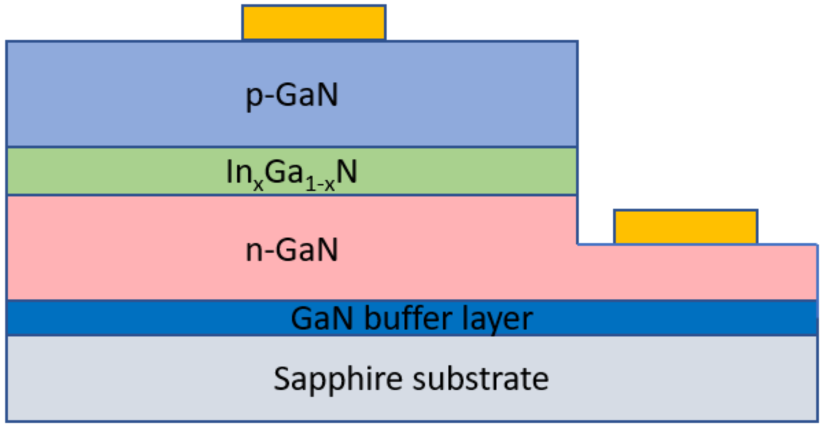
vacuum deposition

Light emitting diodes



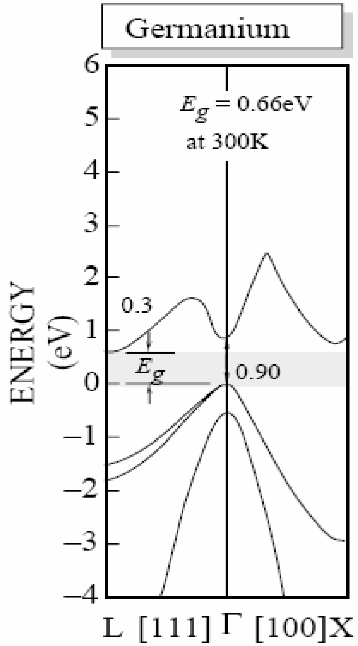




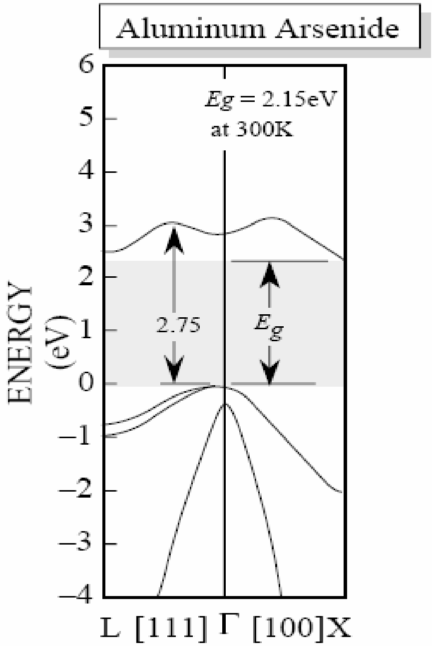


Solid state lighting is efficient.

(a)



(b)



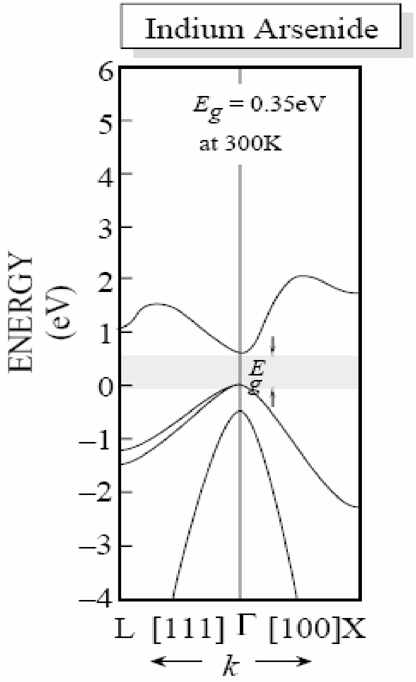
indirect bandgap:
$\Delta k \neq 0$

phonons are emitted

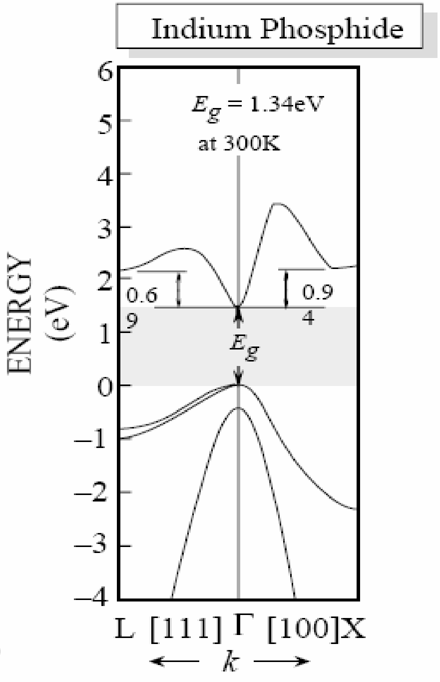
direct bandgap:
$\Delta k = 0$

photons can be emitted

(c)



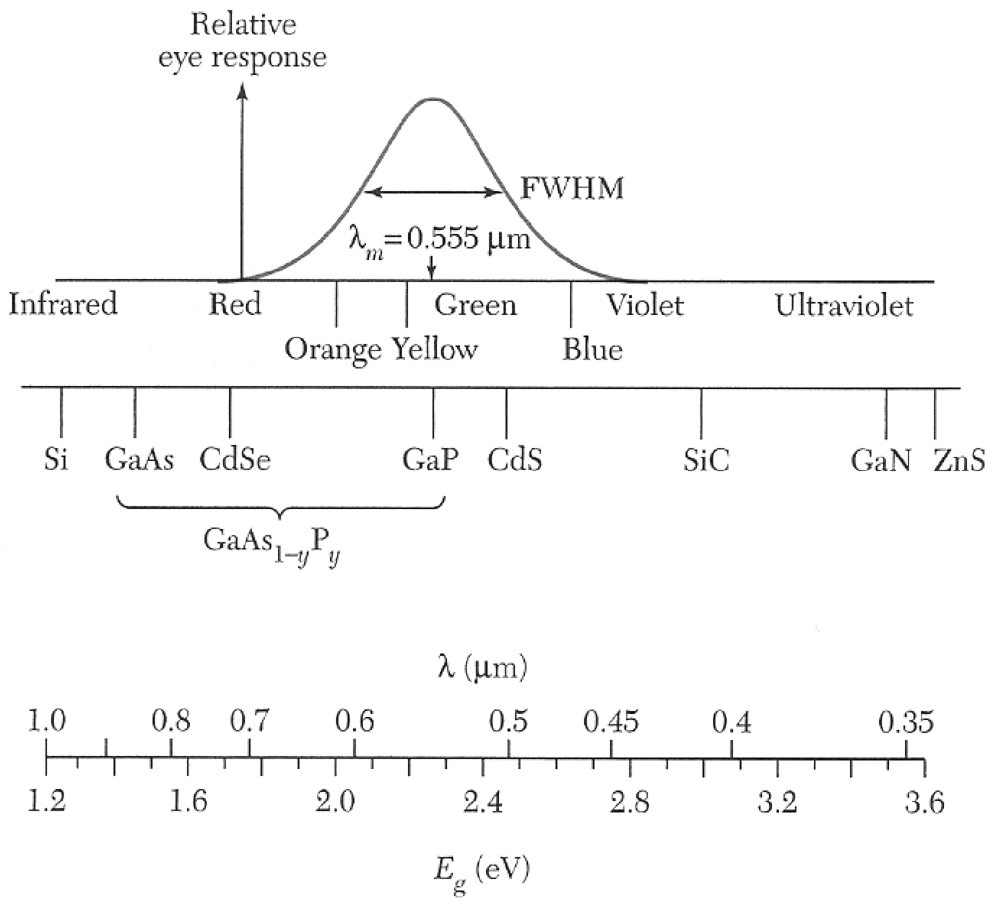
(d)

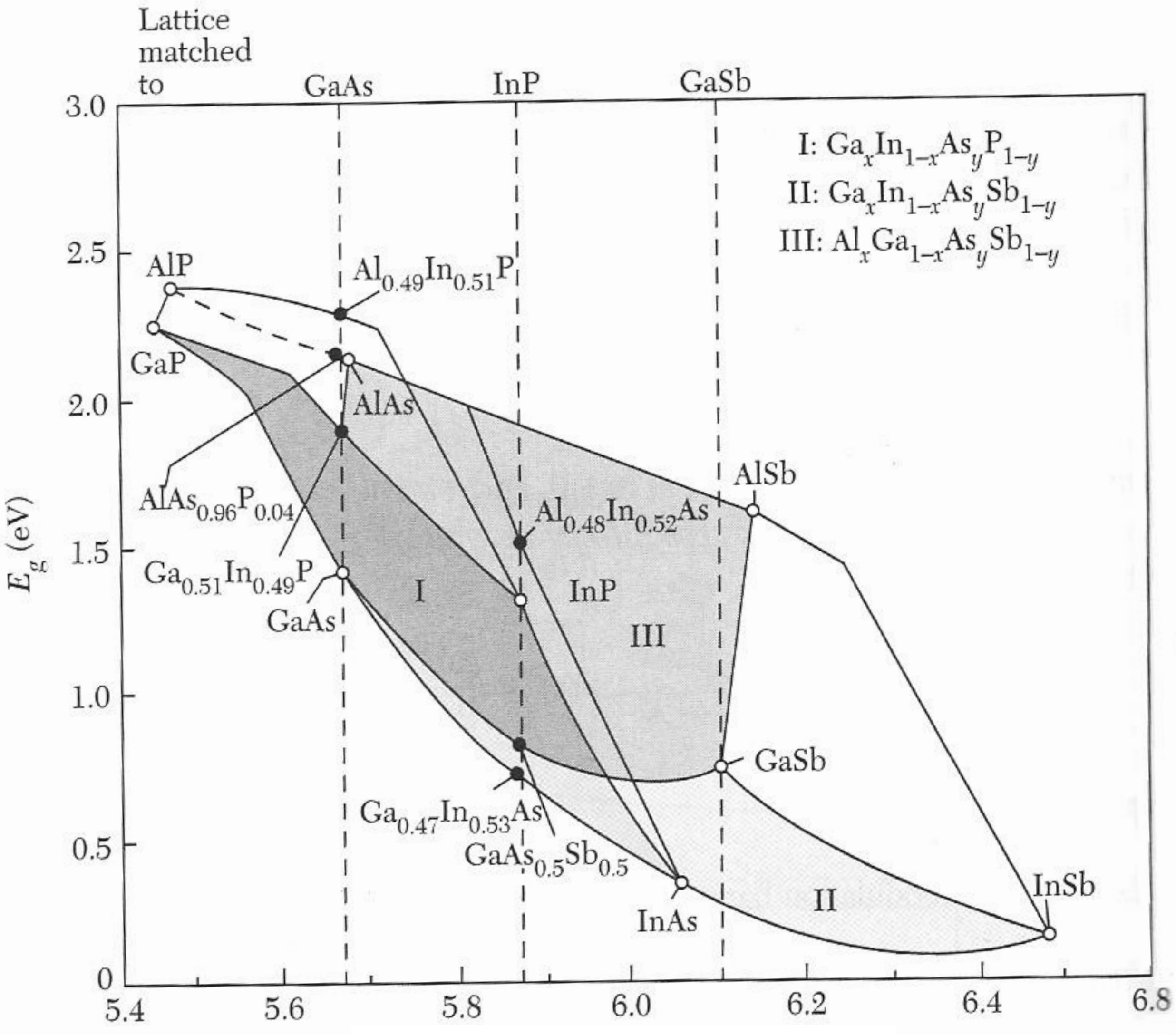


Light emitting diodes

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

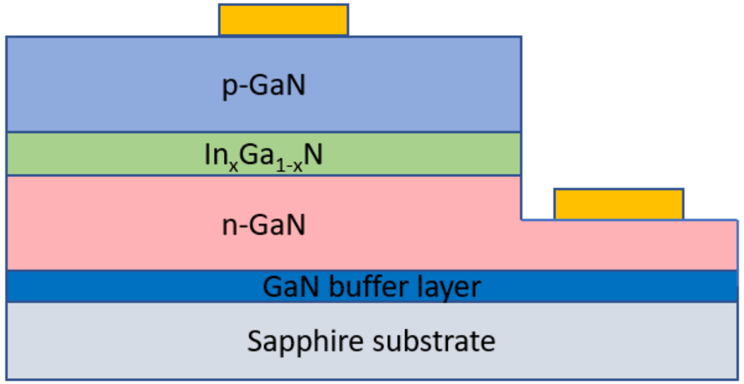
Material	Wavelength (nm)
InAsSbP/InAs	4200
InAs	3800
GaInAsP/GaSb	2000
GaSb	1800
$Ga_xIn_{1-x}As_{1-y}P_y$	1100-1600
$Ga_{0.47}In_{0.53}As$	1550
$Ga_{0.27}In_{0.73}As_{0.63}P_{0.37}$	1300
GaAs:Er,InP:Er	1540
Si:C	1300
GaAs:Yb,InP:Yb	1000
$Al_xGa_{1-x}As$:Si	650-940
GaAs:Si	940
$Al_{0.11}Ga_{0.89}As$:Si	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
GaN	370



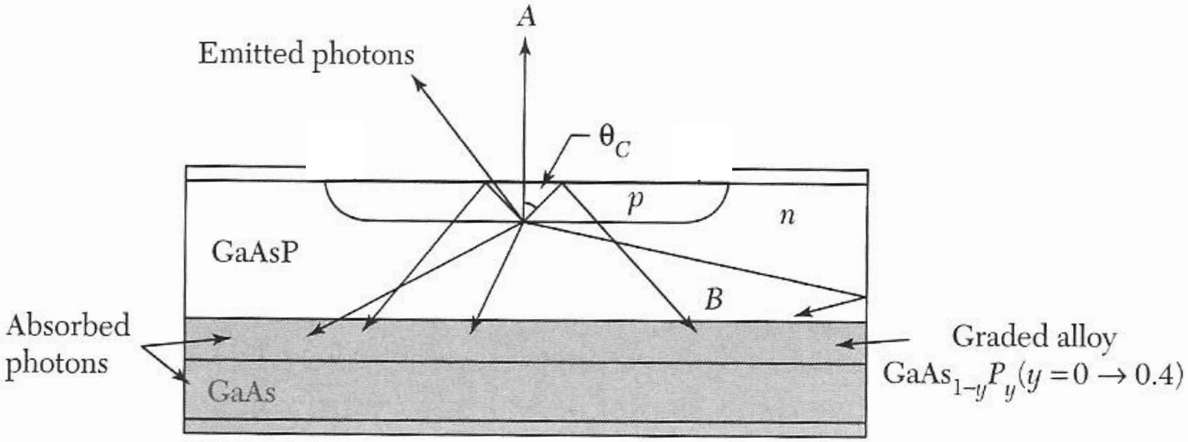


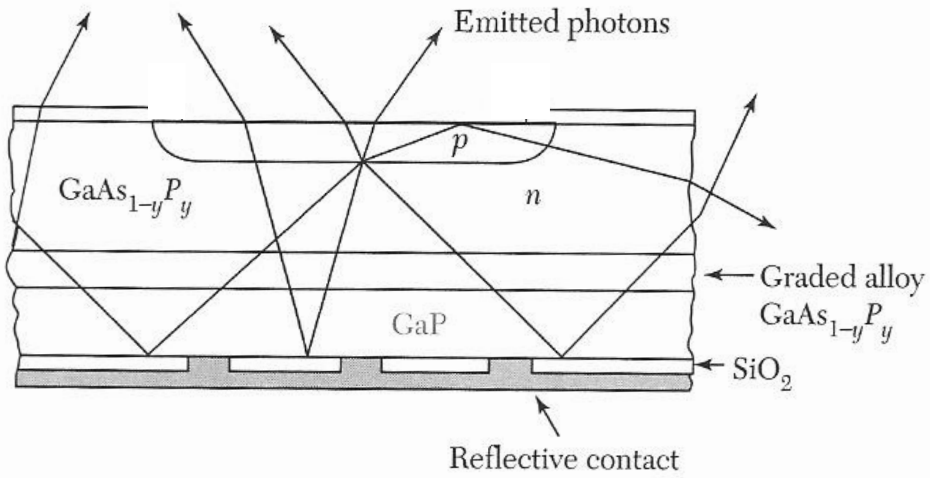
lattice constant (Angstrom)

Light emitting diodes



absorption
reflection
total internal reflection

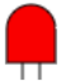




Home
Outline
Introduction
Electrons in crystals
Intrinsic Semiconductors
Extrinsic Semiconductors
Transport
pn junctions
Contacts
JFETs/MESFETs
MOSFETs
Bipolar transistors
Opto-electronics
Lectures
Books
Exam questions
Html basics
TUG students
Student projects
Print version

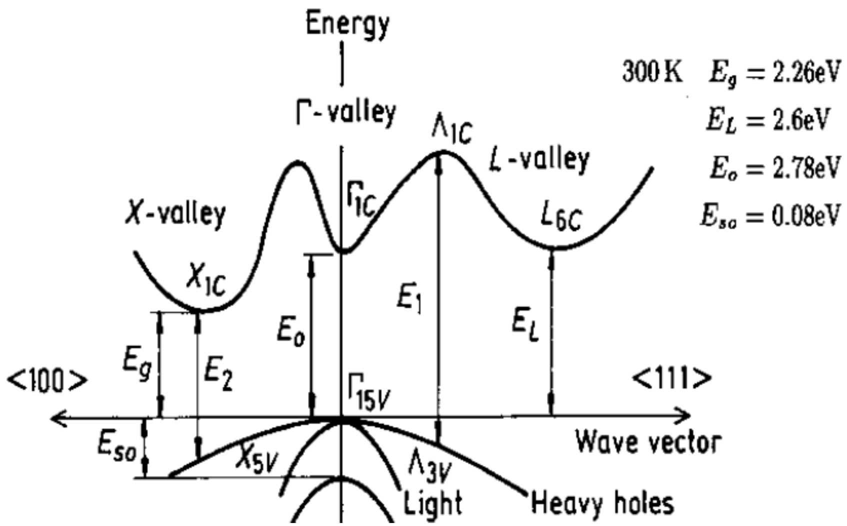
Light Emitting Diode 

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.

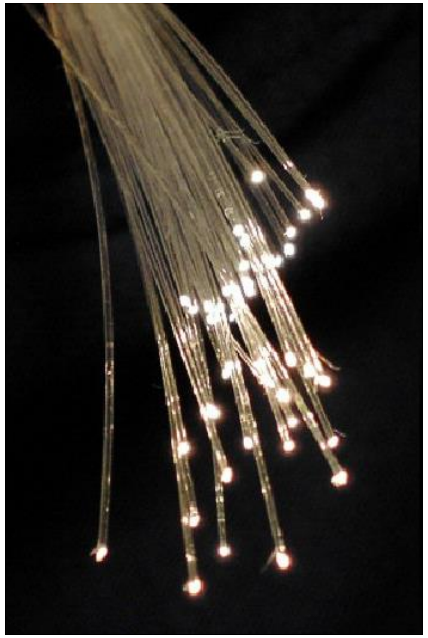
λ = 650 nm - +  $Al_{0.39}Ga_{0.61}As$ $GaAs_{0.39}P_{0.61}$

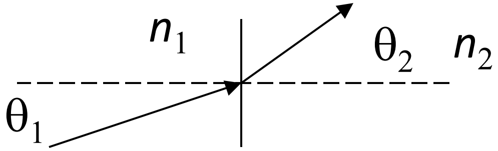
E_g = 1.91 eV visible

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 $E_g \pm k_BT$.

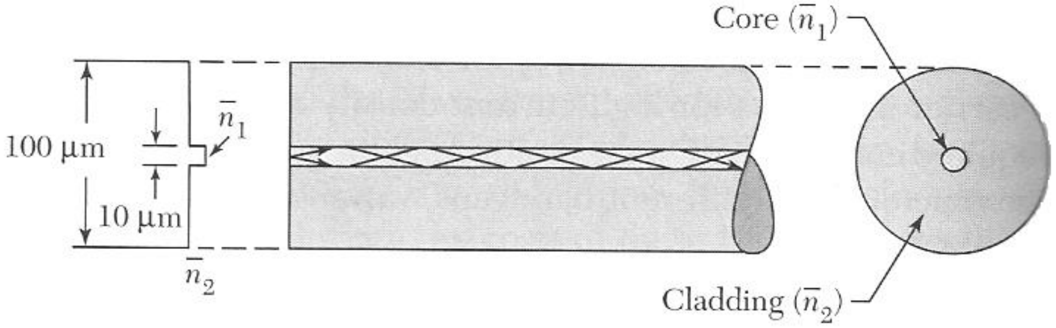


Confinement of light by internal reflection

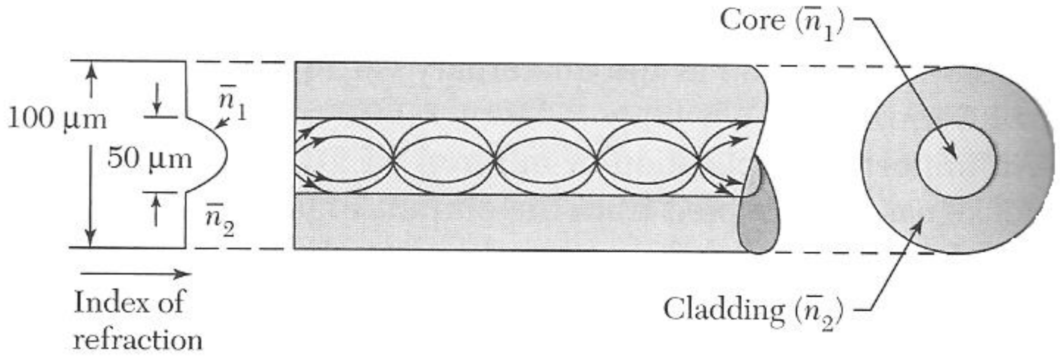


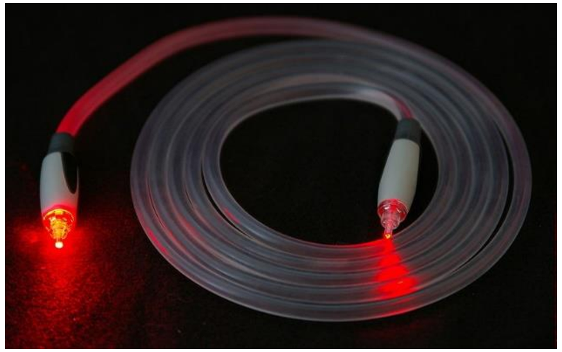


$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$



less pulse spreading for
parabolically graded fiber



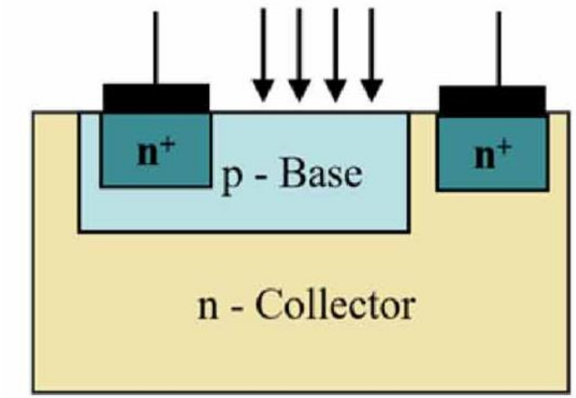


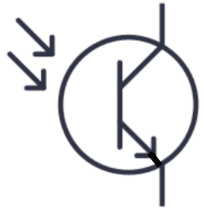
0.6 dB/km at 1.3 μm and 0.2 dB/km at 1.55 μm

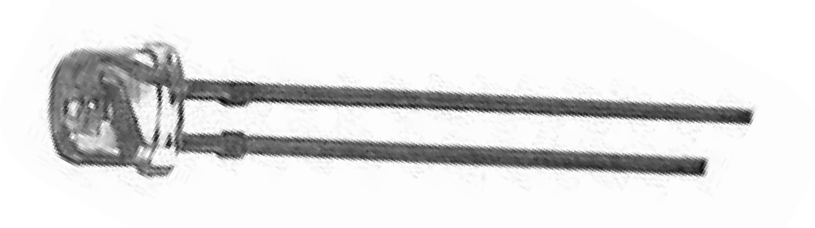
Photo detectors

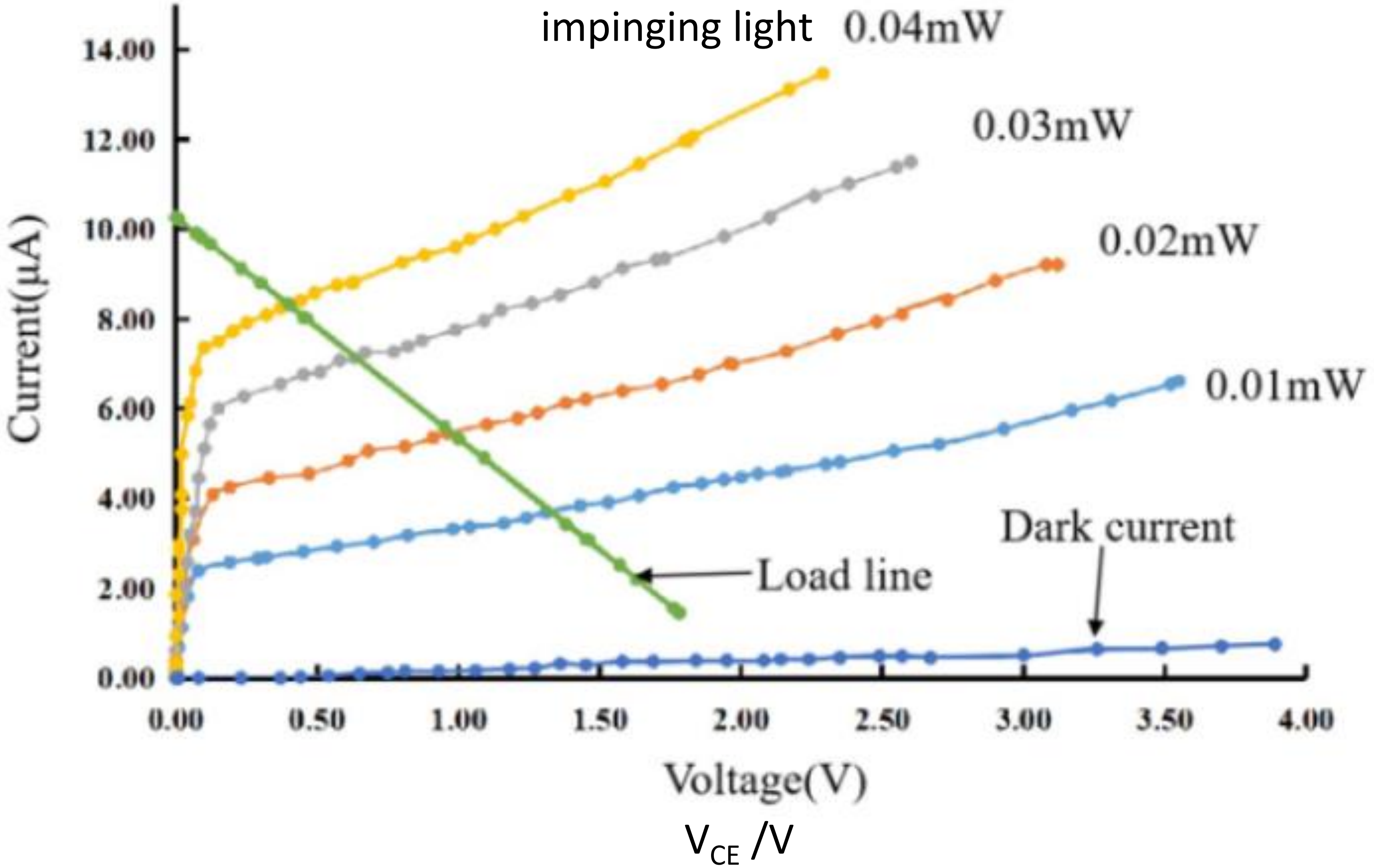
- Intrinsic semiconductor $\sigma = e(\mu_n n + \mu_p p)$ (used in copiers)
- Unbiased pn junction - like a solar cell
- Reverse biased pn junction - smaller capacitance, higher speed, less noise
- Phototransistor:
  light injects carriers into the base -> forward biases the emitter base junction
  high responsivity
  - Ambient light detectors.
  - Active Pixel sensors for automated parking and gesture control (uses time-of-flight to image in 3-D).

Phototransistor







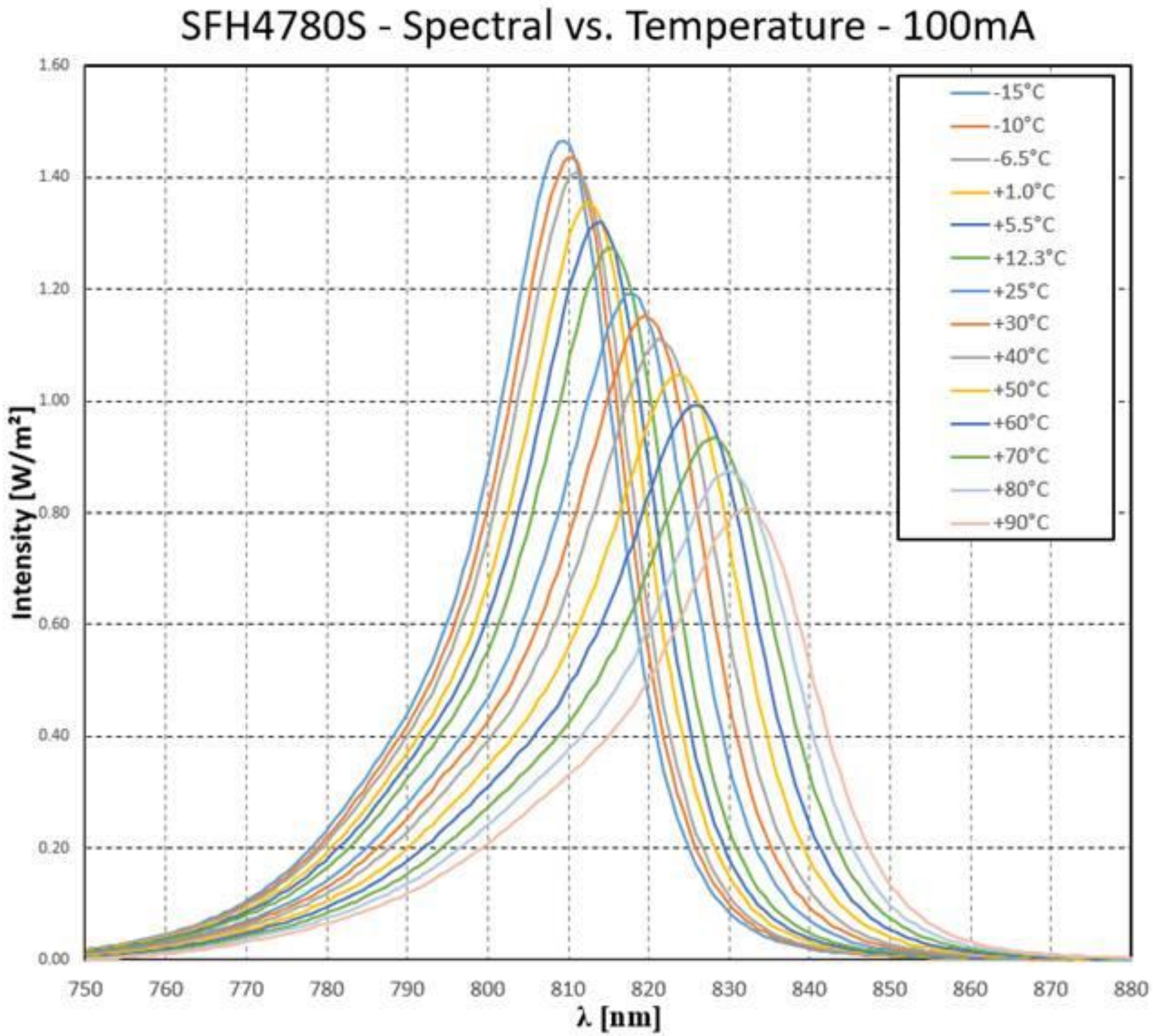


reminiscent to BJT
in common emitter
configuration:

I_B -> I_{photo}

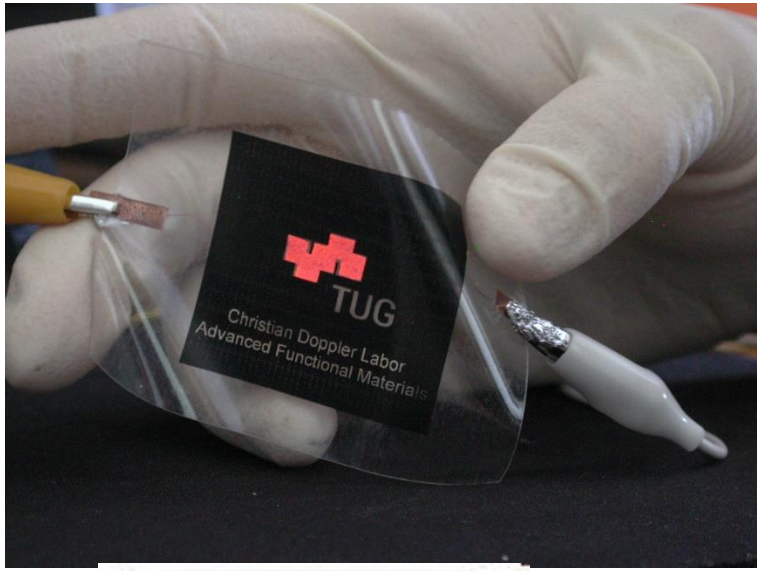
images: DOI: 10.1088/1361-6552/ace8e8

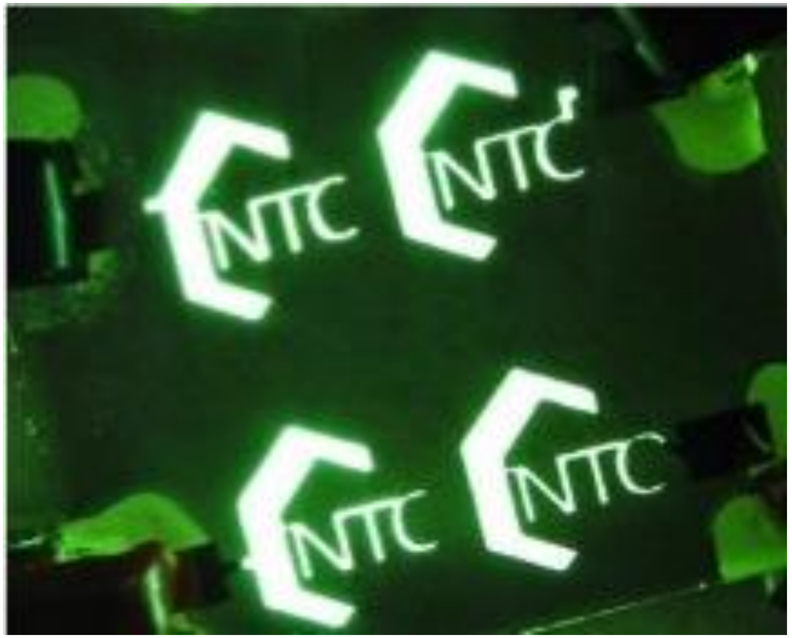
IR LED



Measurement by Jan Enenkel

OLEDs





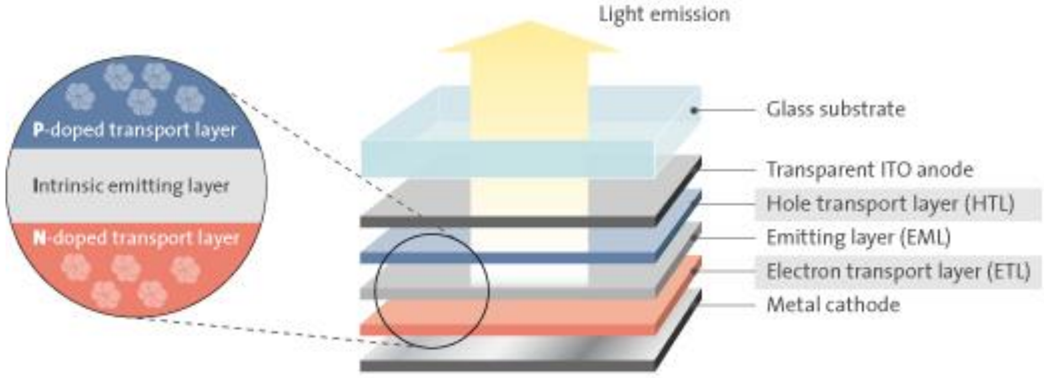
Galaxy Tab

Encapsulation technology

Organic light emitting diodes

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

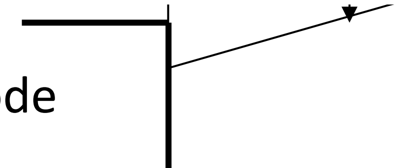
Cathode is typically a low work function material Al, Ca - injects electrons



ITO - injects holes

-

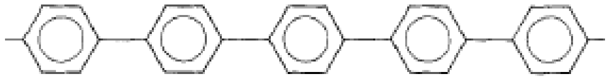
thode



Anode

Electroluminescence in poly(p-phenylene)

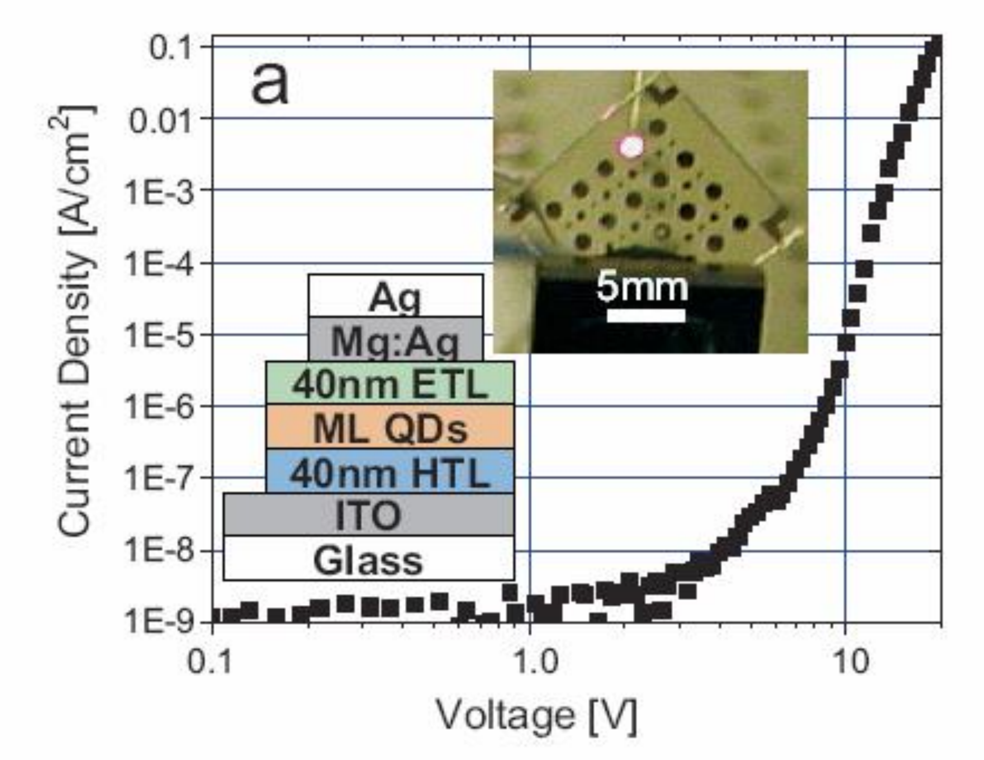
Prof. Günther Leising

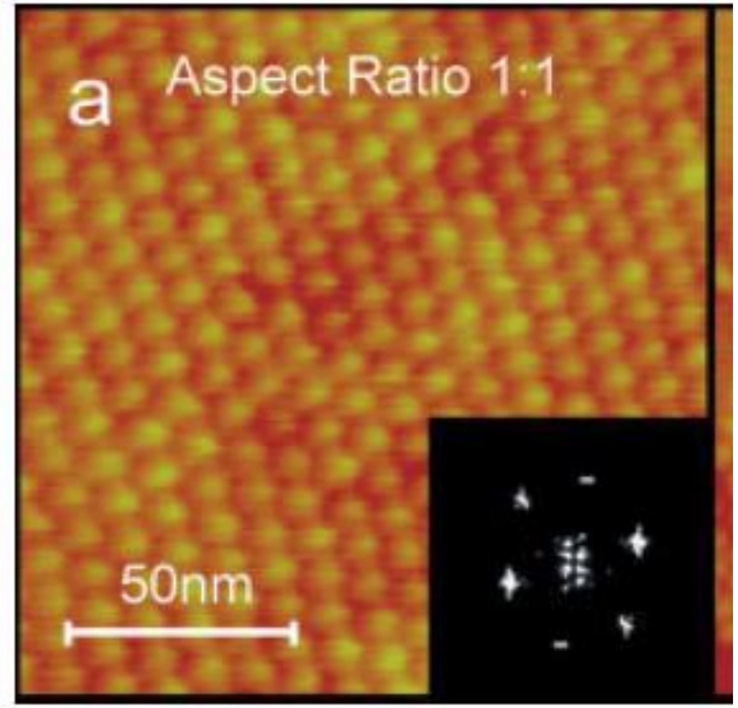


In 1992, Leising et al. for the first time reported on blue electroluminescence from OLEDs containing poly(p-phenylene) (PPP).

G. Grem, G. Leditzky, B. Ullrich and G. Leising, Adv. Mater. vol.4 p. 36 (1992).

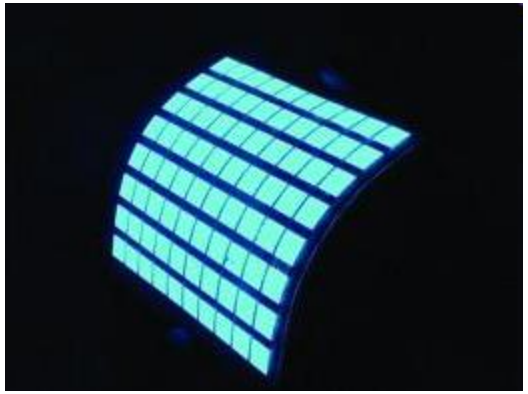
Q-dot LEDs





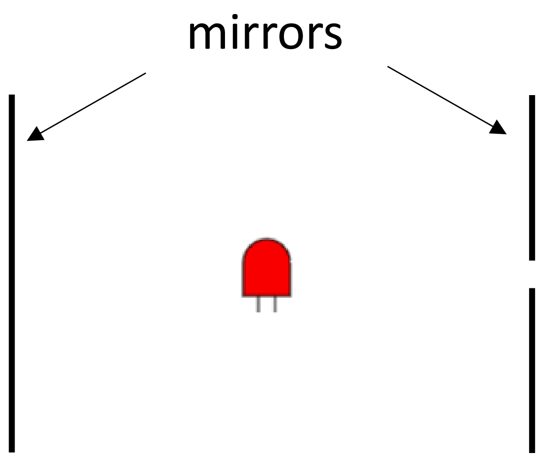
Coe-Sullivan, et al. Advanced Functional Materials, 10.1002/adfm.200400468

Efficient lighting

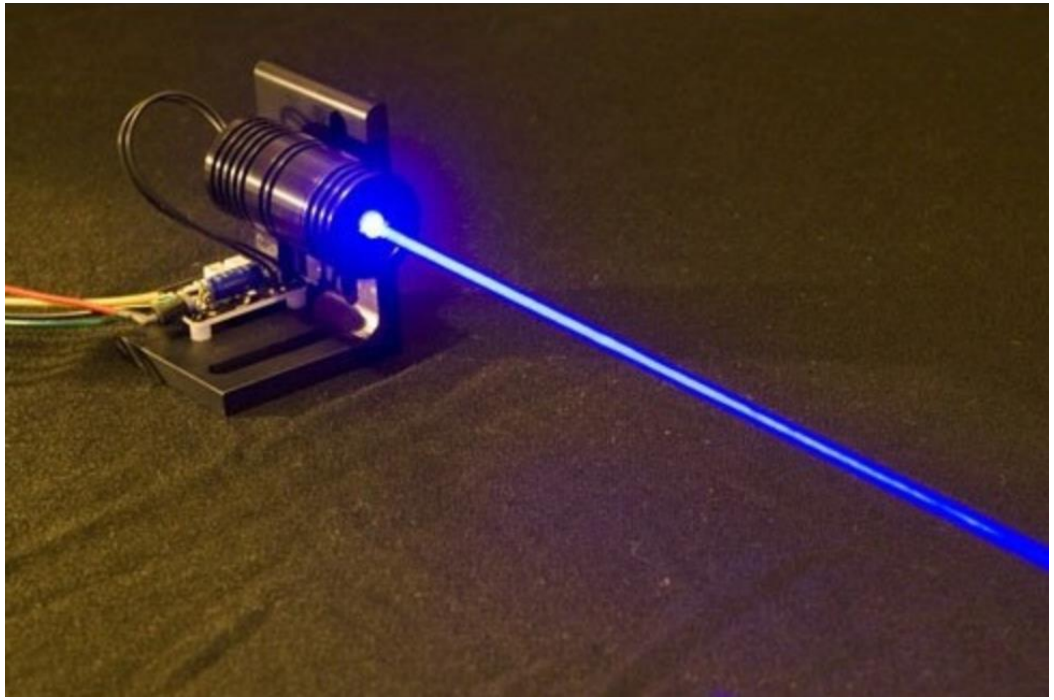


Very efficient
Many colors possible
No toxic chemicals

Laser Diodes

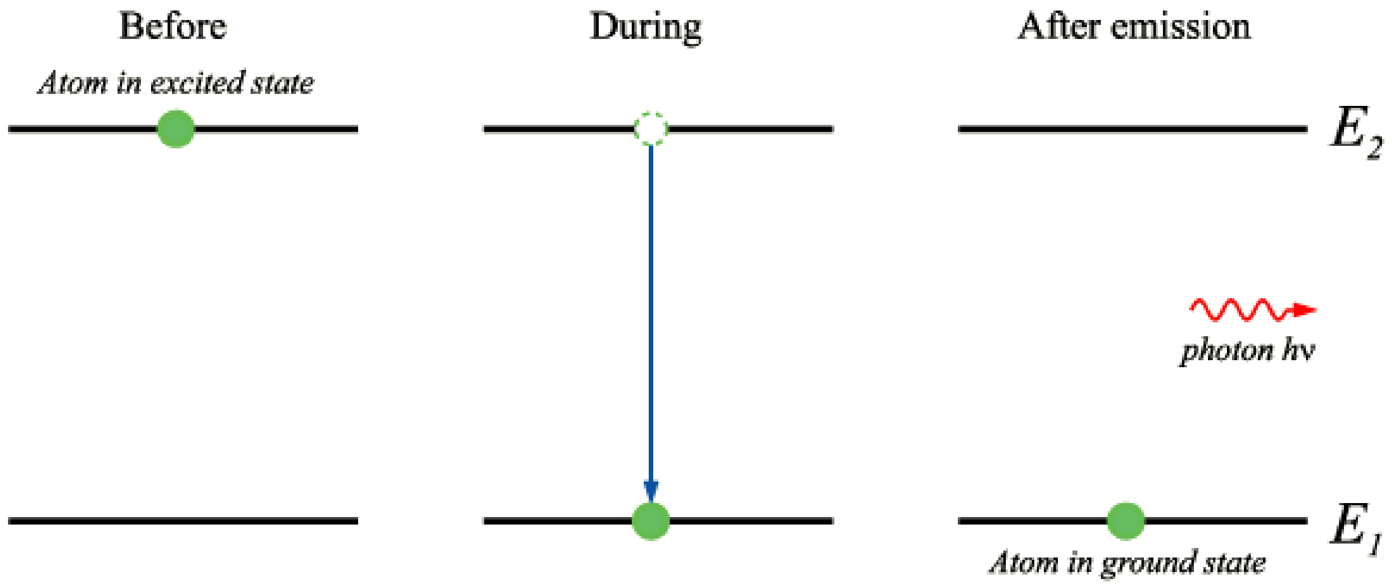


Laser diodes



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

Spontaneous emission

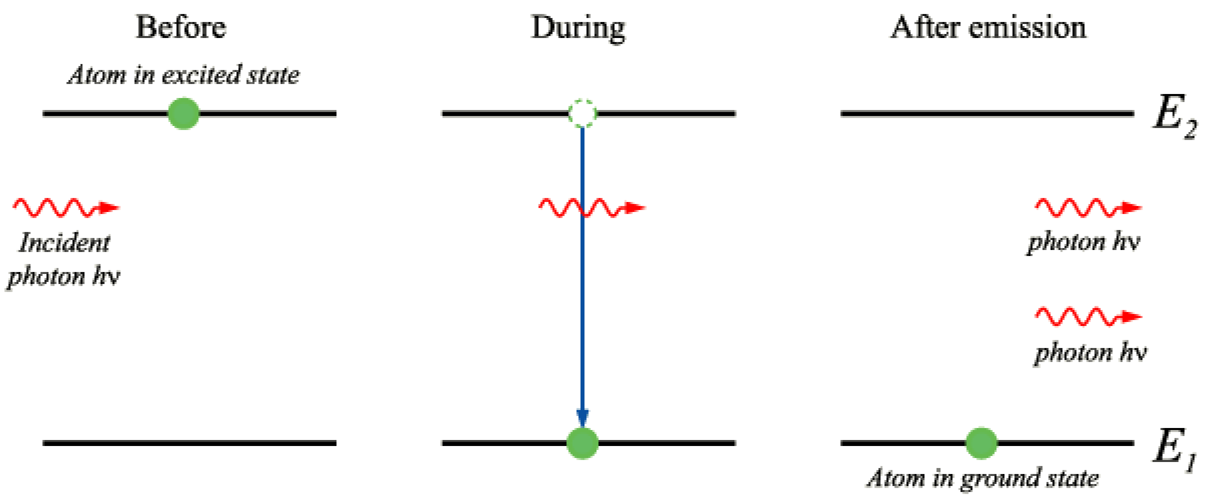


$$h\nu = E_2 - E_1$$

- **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.**

- **Recombination time $\tau = 1/W$ W …Recombination rate**

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

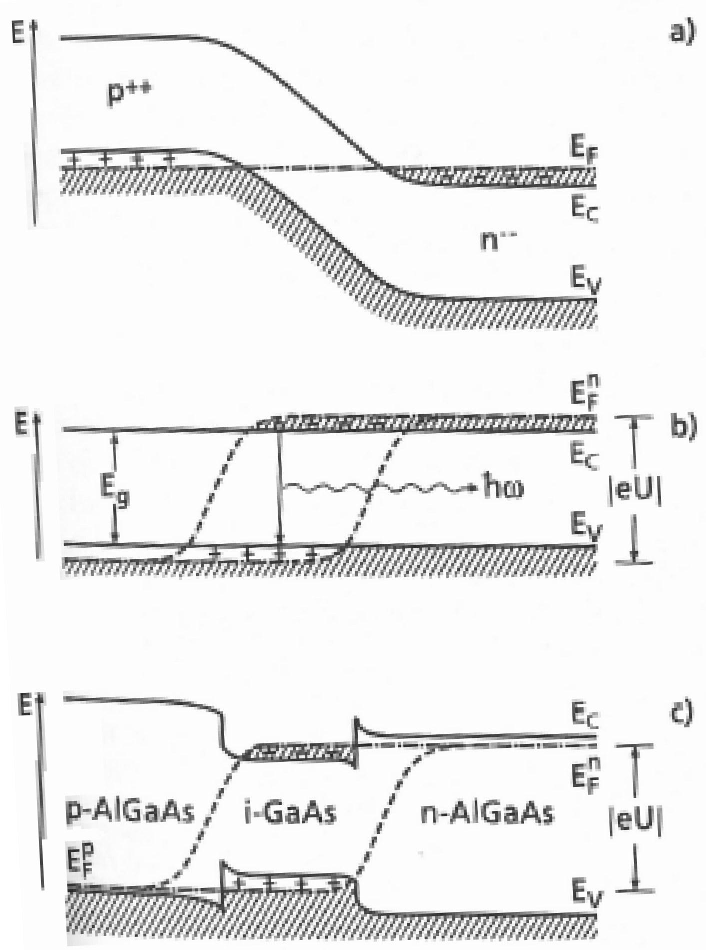
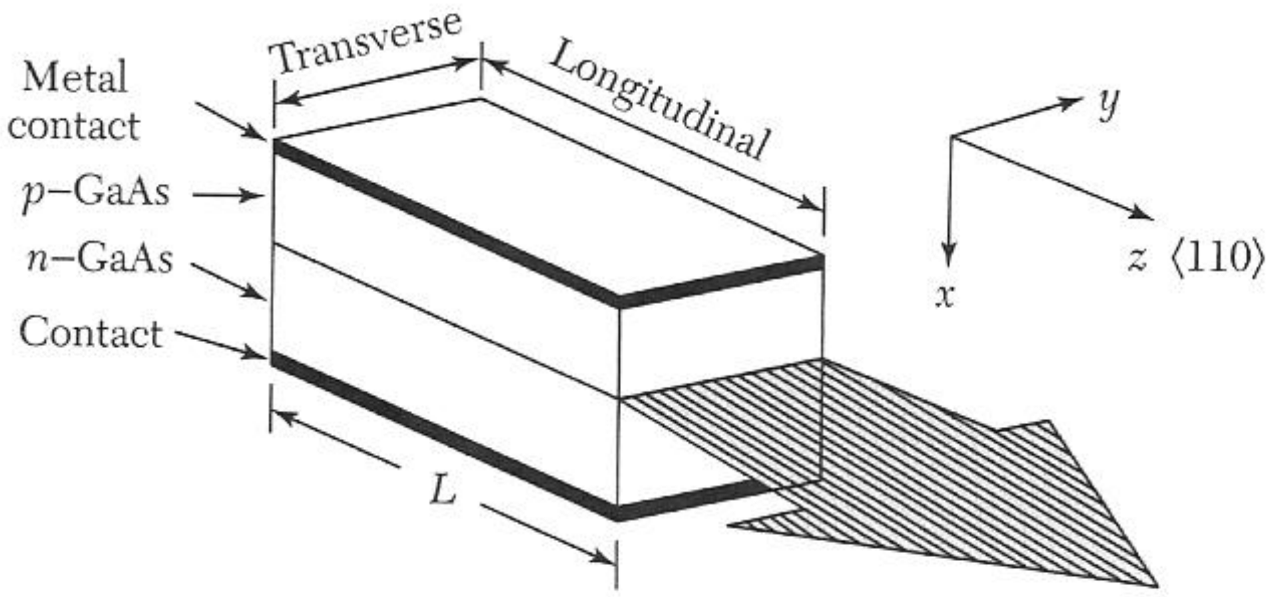


Fig. 12.37. Electronic band schemes $E(x)$ of *pn*-semiconductor laser structures along a direction x perpendicular to the layer structure: **(a)** Degenerately doped $p^{++}n^{--}$ junction without external bias (thermal equilibrium); **(b)** same $p^{++}n^{--}$ junction with maximum bias U in forward 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*

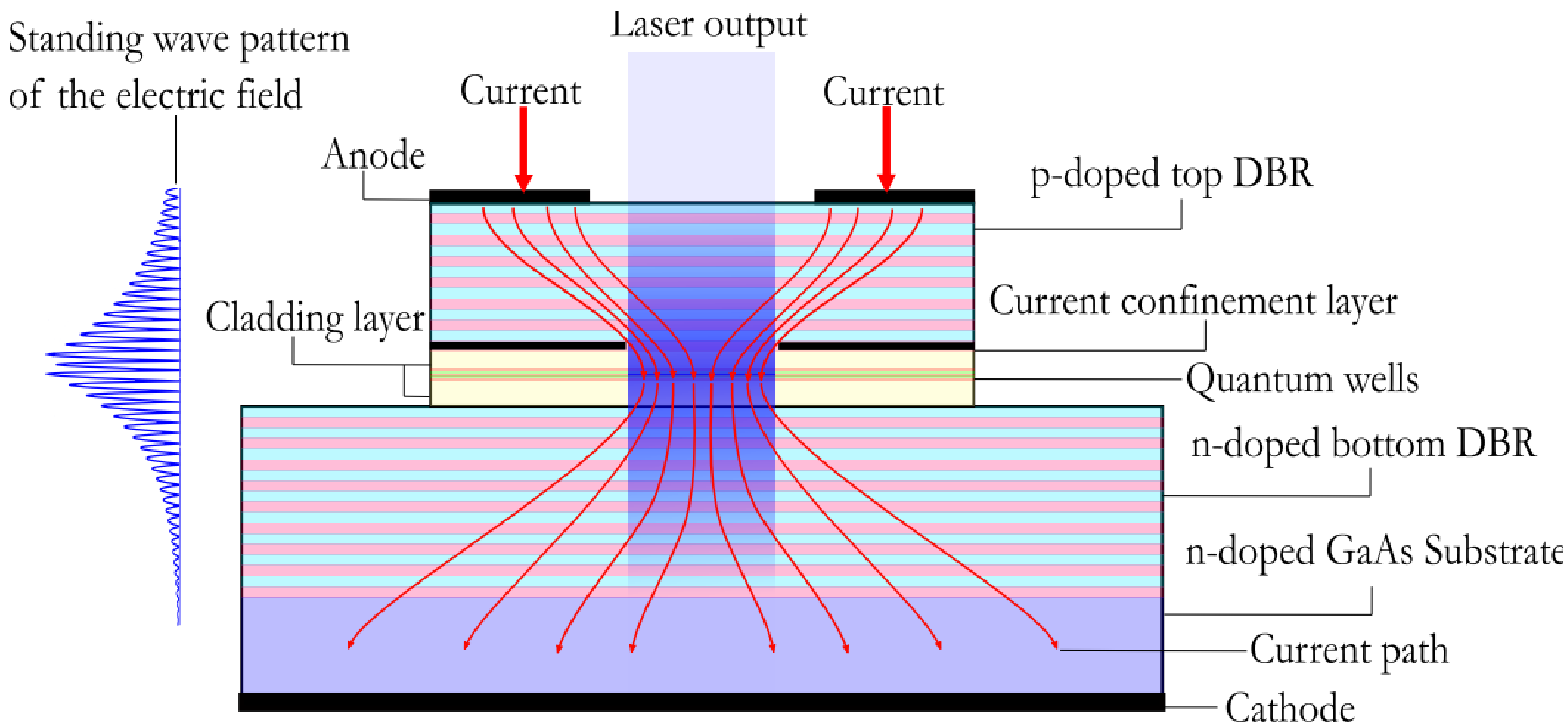
Laser diode

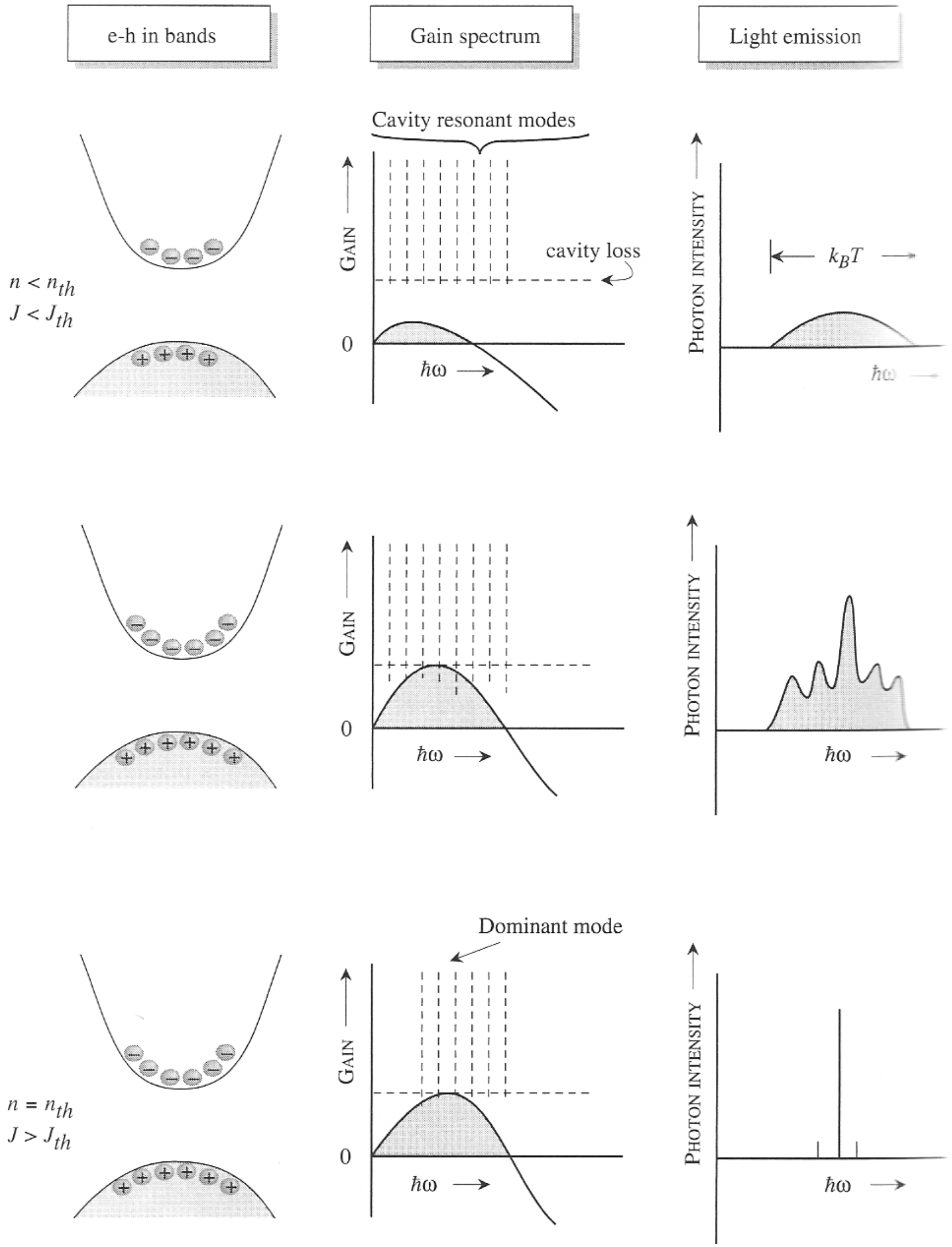


(a)

The faces of the crystal are cleaved to make mirrors.

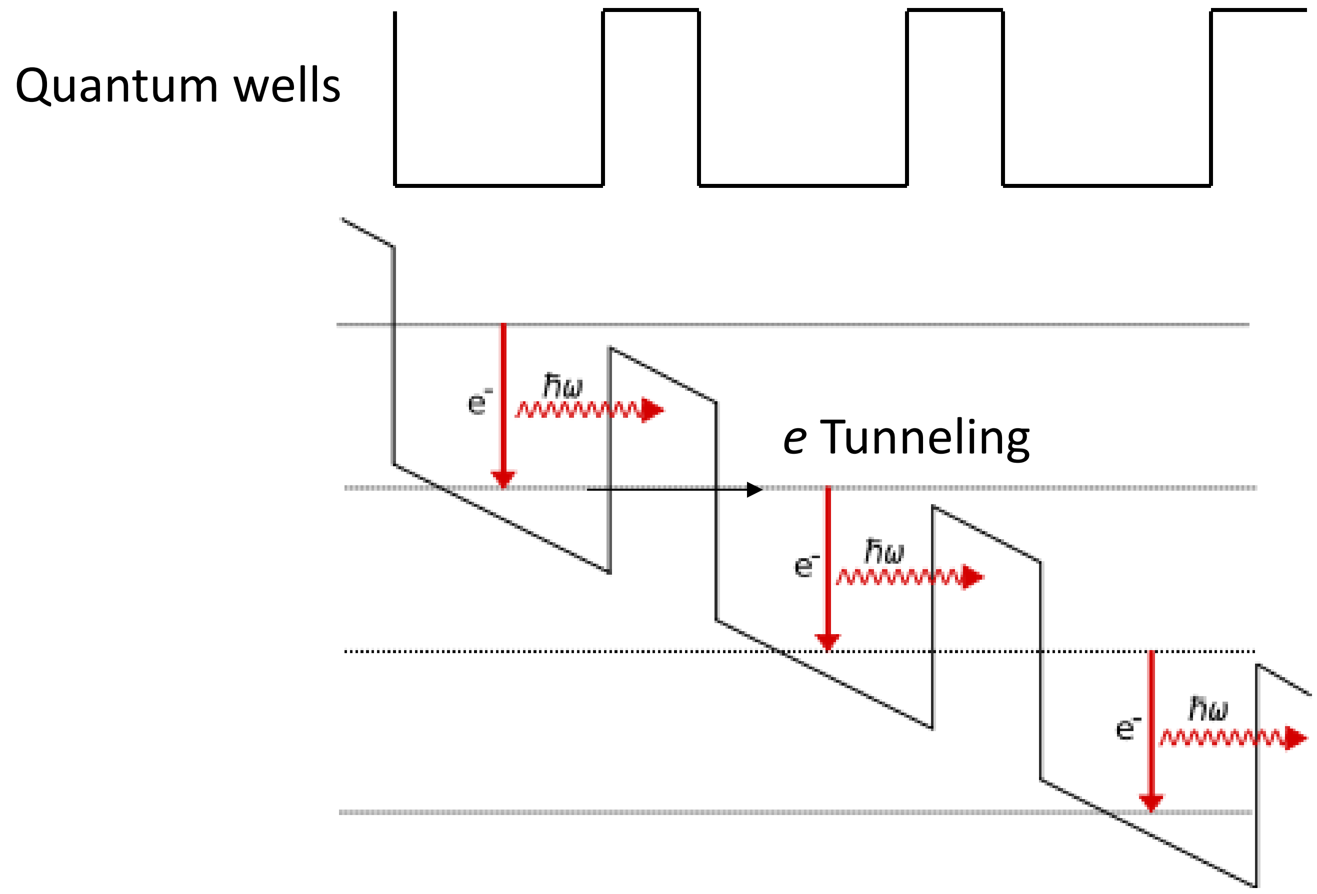
Vertical-cavity surface-emitting laser (VCSEL)





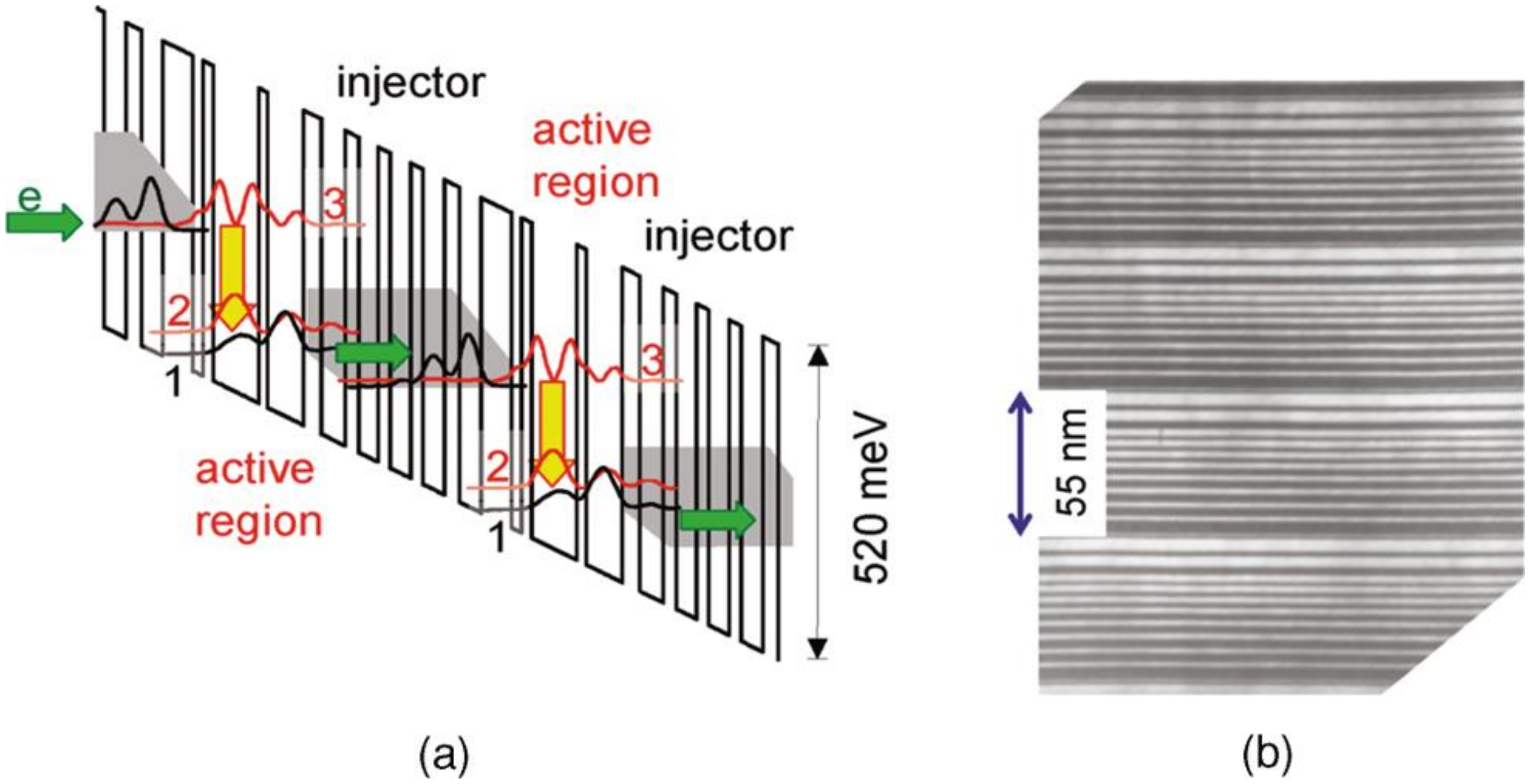
e-h in bands
Gain spectrum
Light emission
Cavity resonant modes
cavity loss
$n < n_{th}$
$J < J_{th}$
GAIN
0
$\hbar\omega$
PHOTON INTENSITY
k_BT
Dominant mode
$n = n_{th}$
$J > J_{th}$

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 mm).
Many colors can be made with one materials system.
Window in atmosphere at 5 mm used for point-to-point communications.

Quantum cascade lasers



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