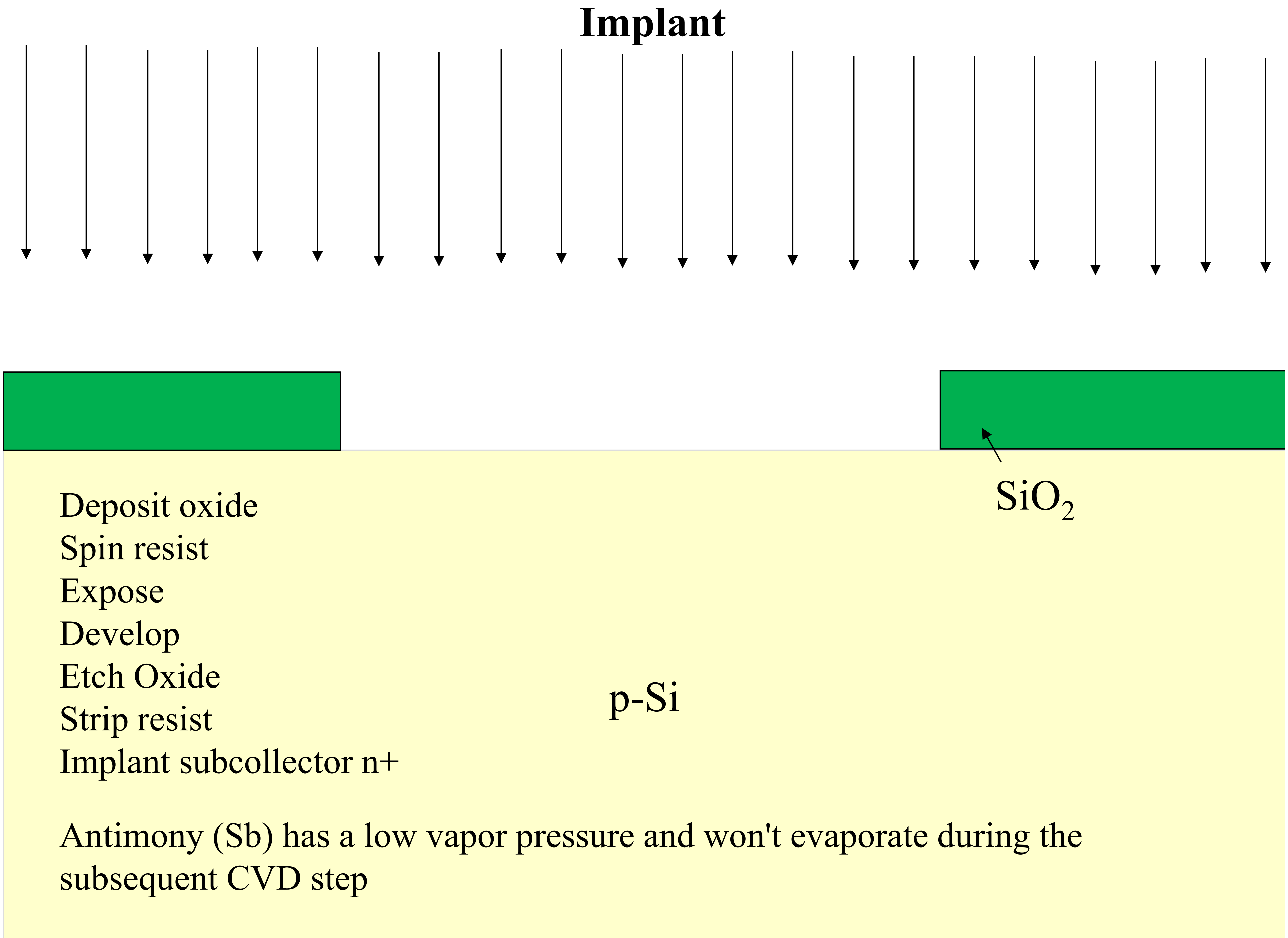
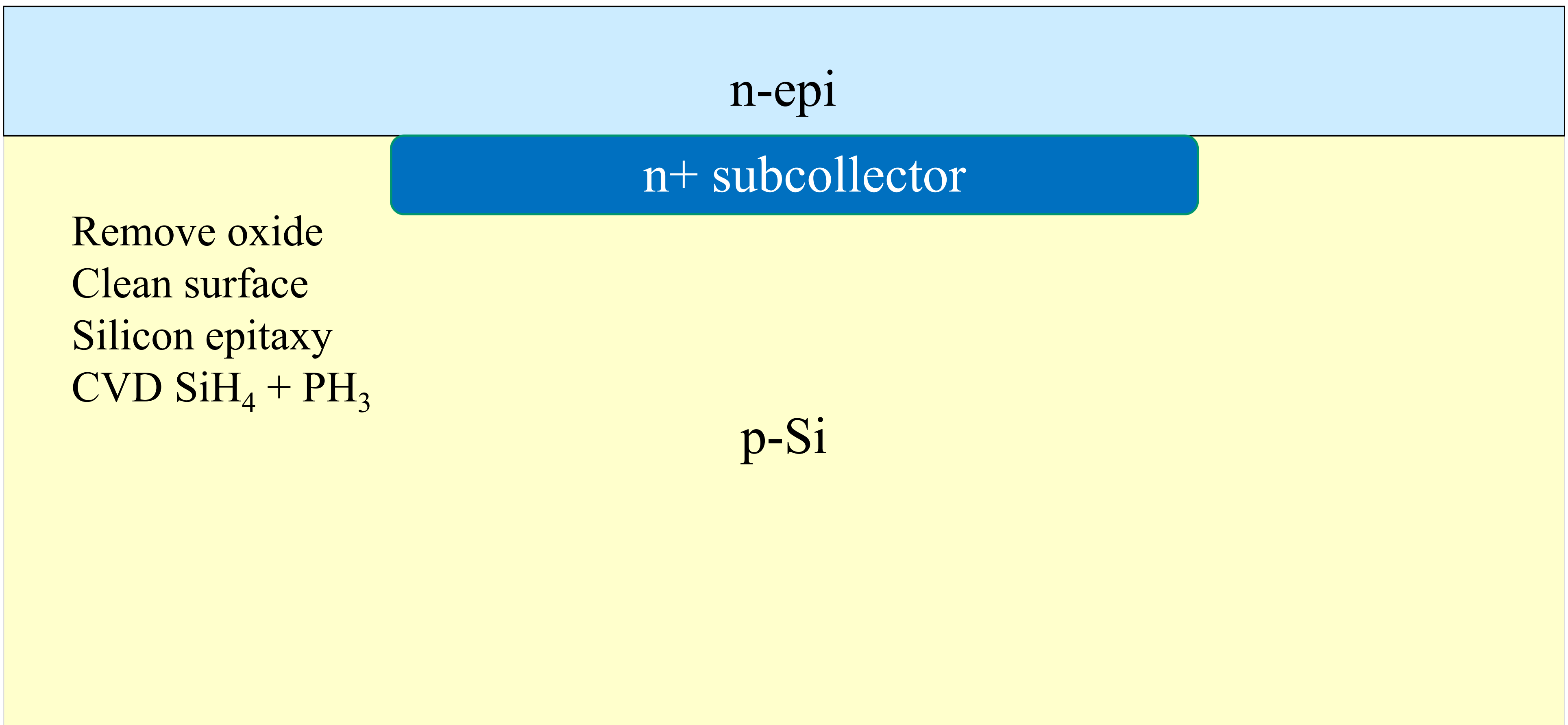
14. Optoelectronics

Jan. 23, 2019

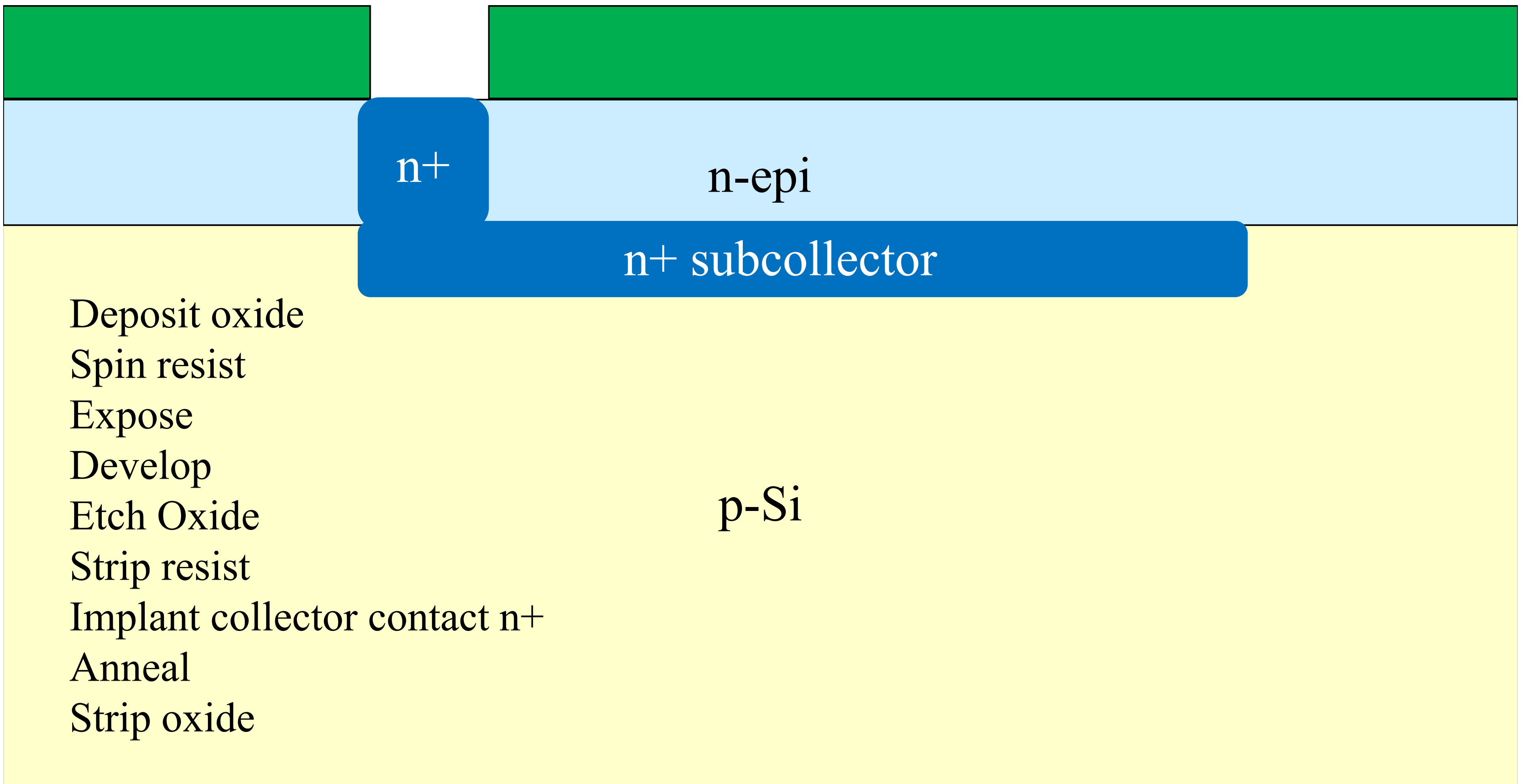

Implant
SiO2
Deposit oxide
Spin resist
Expose
Develop
Etch Oxide
Strip resist
Implant subcollector n+
p-Si
Antimony (Sb) has a low vapor pressure and won't evaporate during the subsequent CVD step

Epi-growth

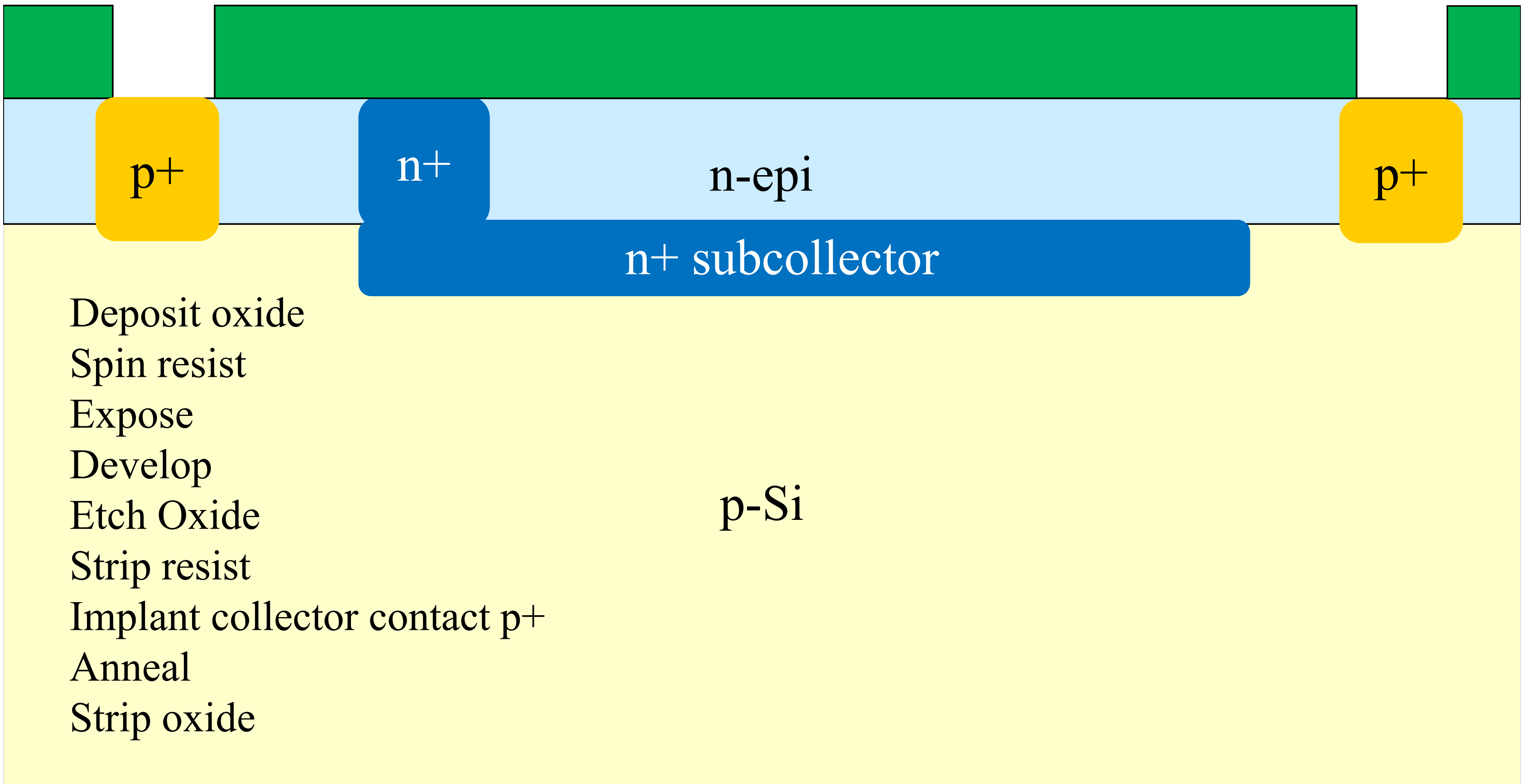


n-epi
n+ subcollector
Remove oxide
Clean surface
Silicon epitaxy
CVD $SiH_4 + PH_3$
p-Si

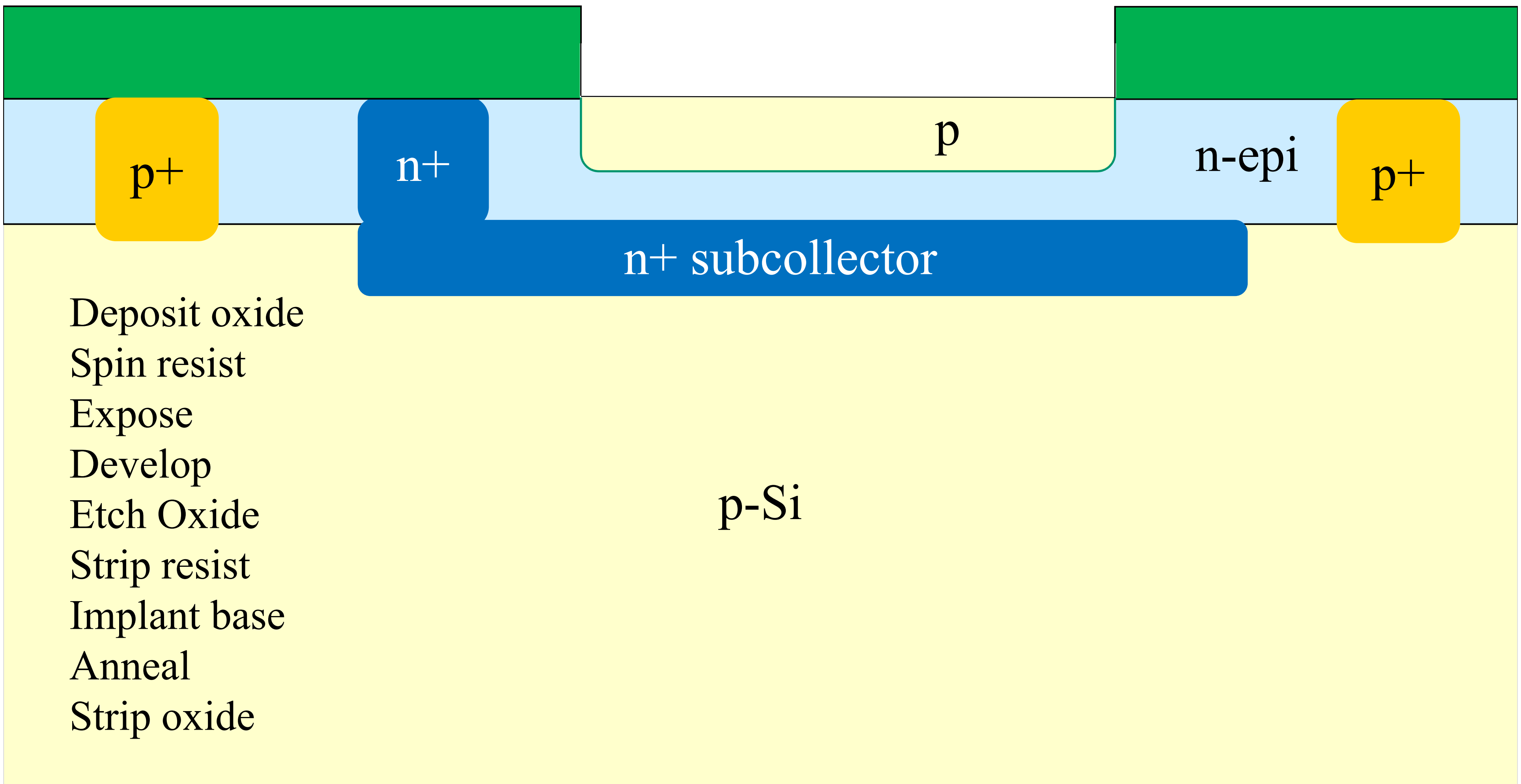
Collector Contact



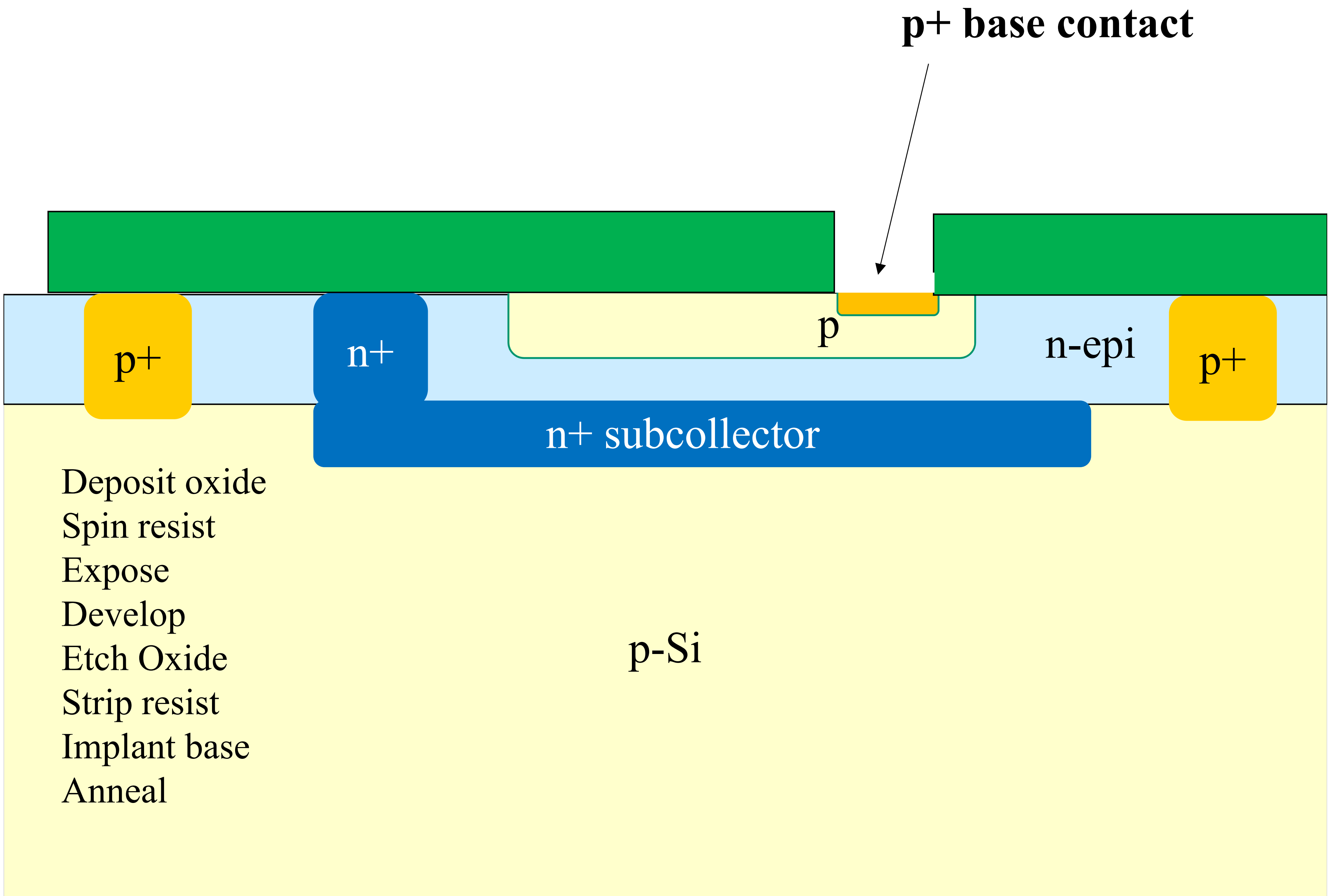
Guard ring

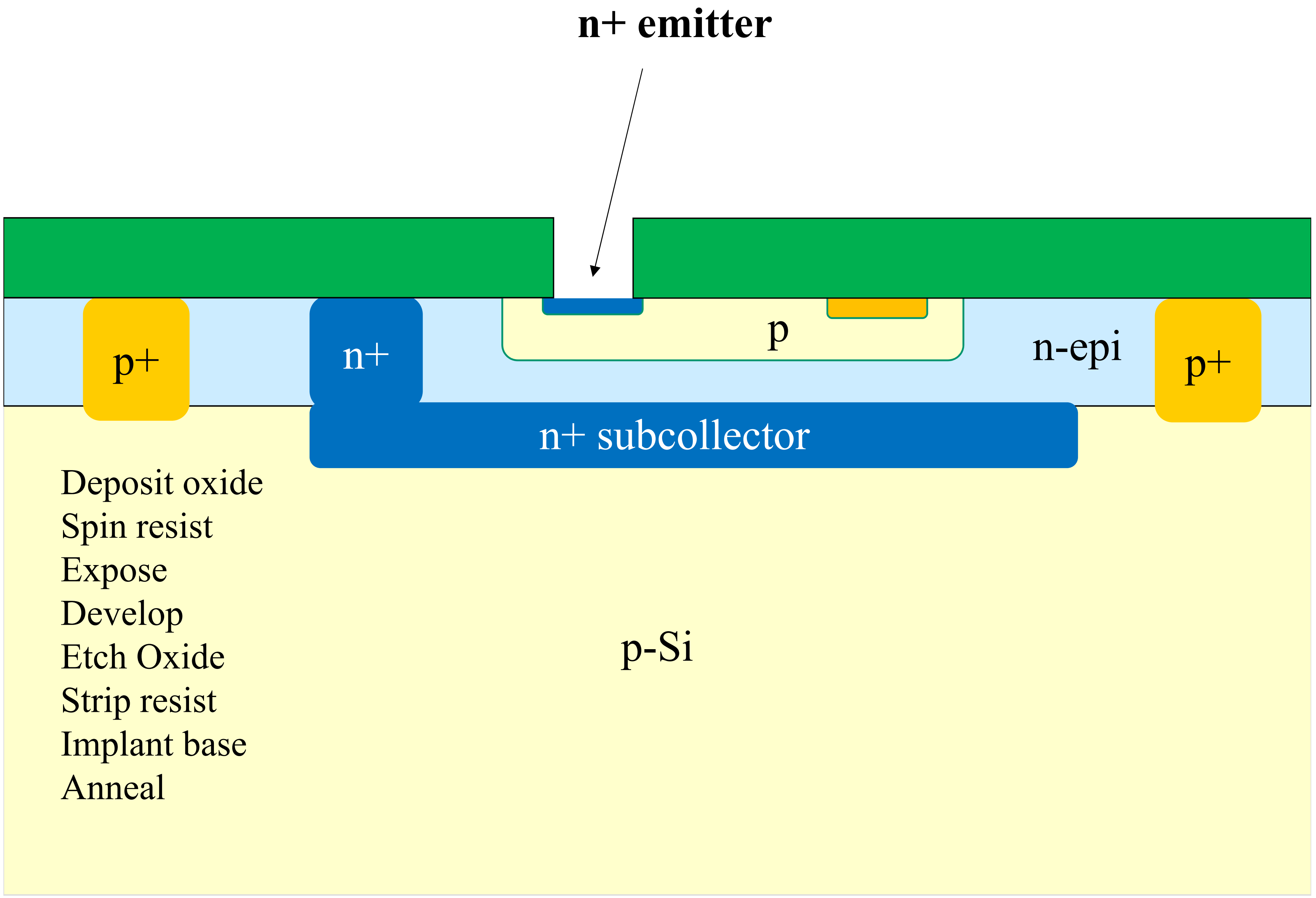

p+
n+
n-epi
p+
n+ subcollector
Deposit oxide
Spin resist
Expose
Develop
Etch Oxide
Strip resist
Implant collector contact p+
Anneal
Strip oxide
p-Si

p-well



p+
n+
p
n-epi
p+
n+ subcollector
Deposit oxide
Spin resist
Expose
Develop
Etch Oxide
Strip resist
Implant base
Anneal
Strip oxide
p-Si


p+ base contact
p+
n+
p
n-epi
p+
n+ subcollector
Deposit oxide
Spin resist
Expose
Develop
Etch Oxide
Strip resist
Implant base
Anneal
p-Si


n+ emitter
p+
n+
p
n-epi
p+
n+ subcollector
Deposit oxide
Spin resist
Expose
Develop
Etch Oxide
Strip resist
Implant base
Anneal
p-Si

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

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

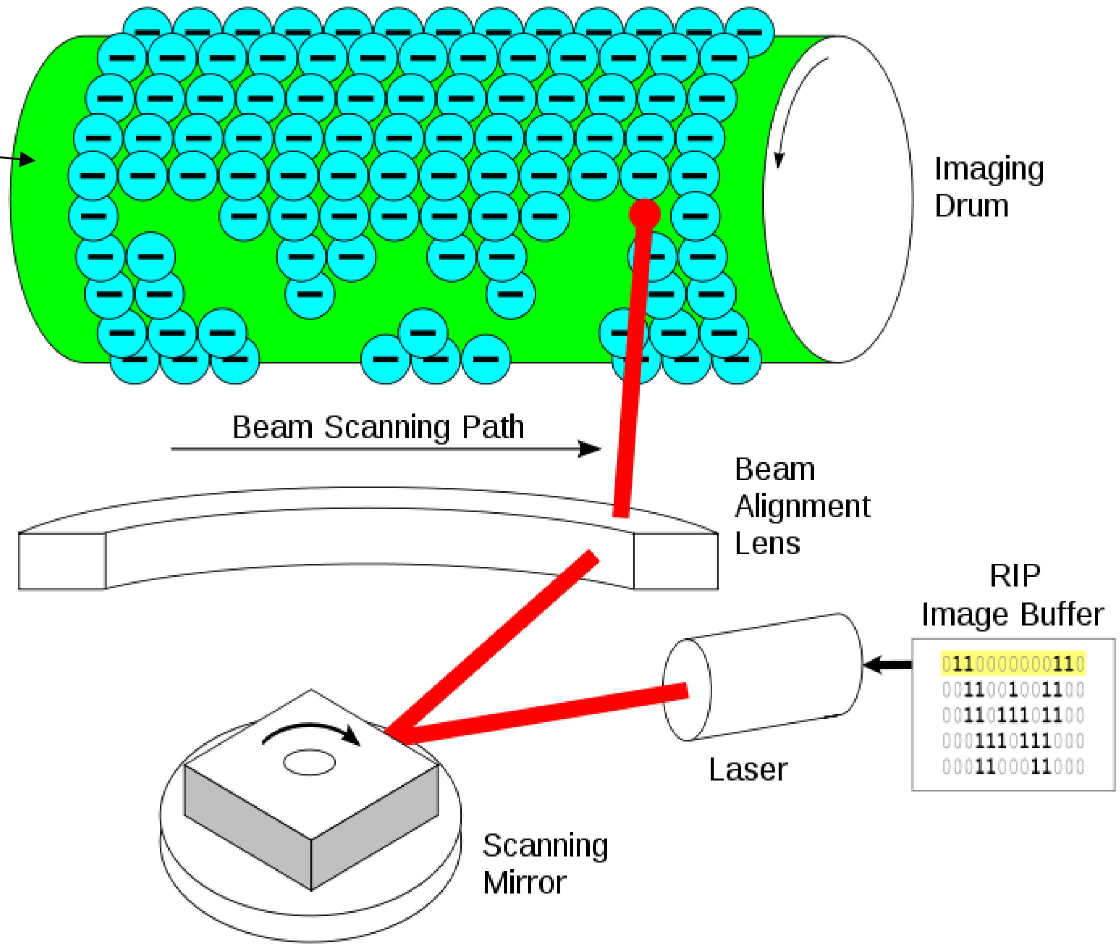
Phototransistor - light injects carriers into the base. This forward biases the emitter base junction. High responsivity.

Ambient light detectors.

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

Laser printer

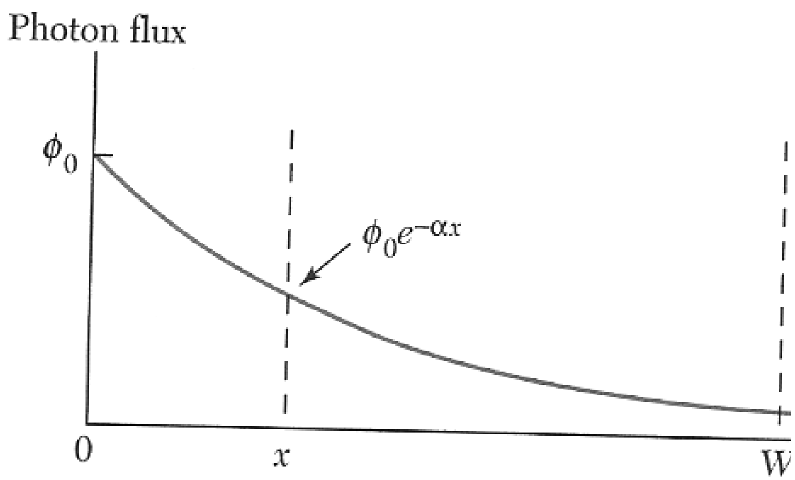
semiconducting
photoconductor



https://en.wikipedia.org/wiki/Laser_printing

Absorption

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

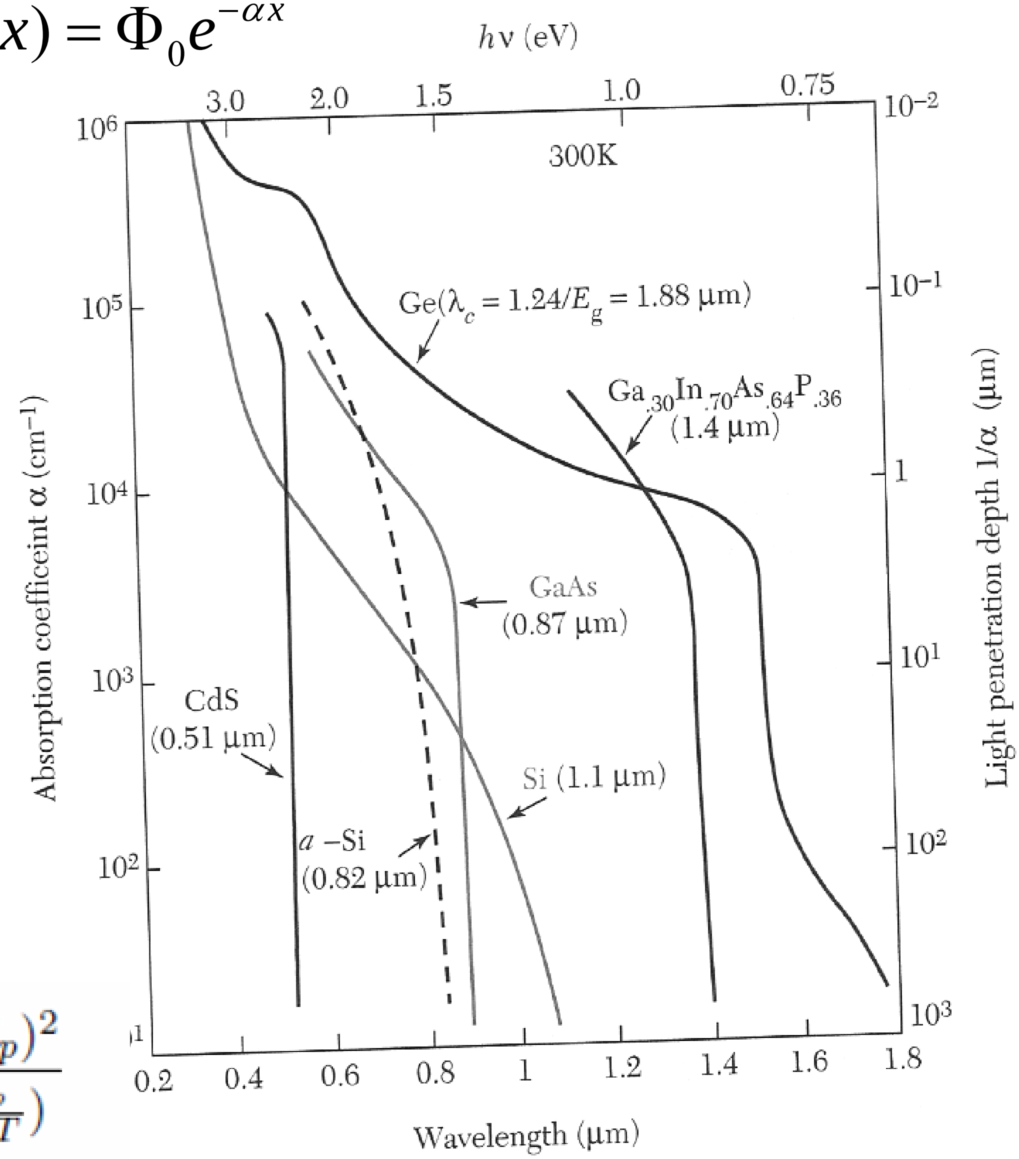


Sharp absorption edge for direct bandgap materials

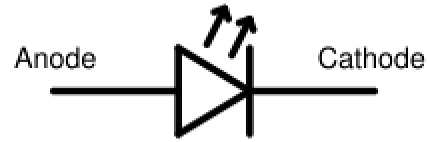
$$\alpha \approx 3.5 \times 10^6 \left(\frac{m_r^*}{m_0} \right)^{3/2} \frac{\sqrt{\hbar\omega - E_g}}{\hbar\omega} \quad \text{cm}^{-1}$$

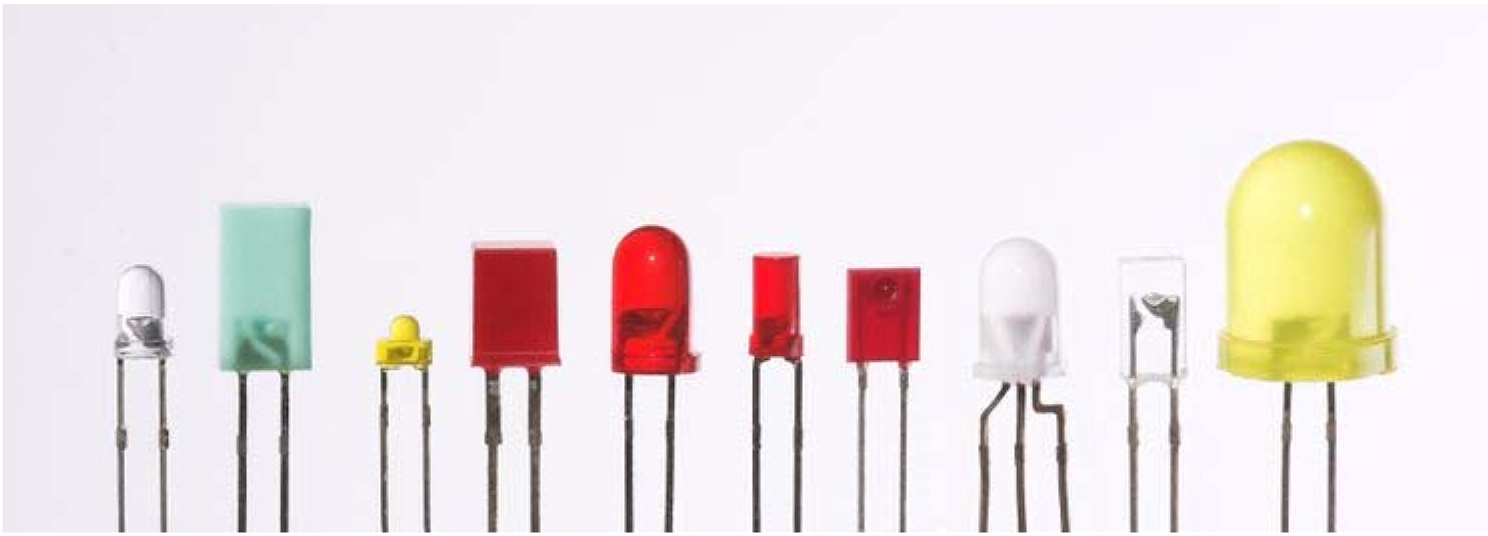
direct bandgap   indirect bandgap

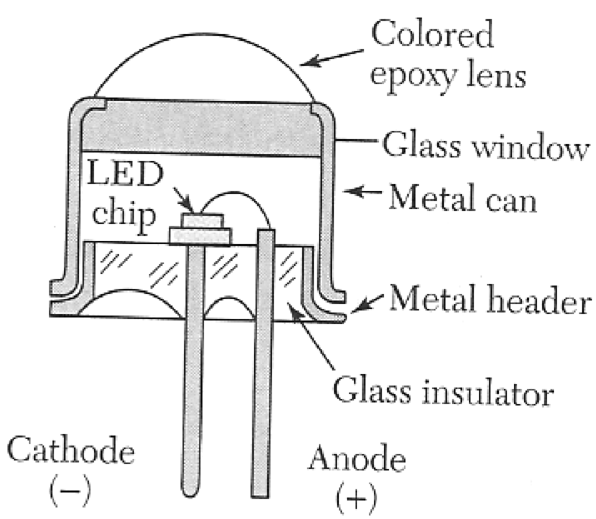
$$\alpha \propto \frac{(h\nu - E_g + E_p)^2}{exp(\frac{E_p}{k_B T}) - 1} + \frac{(h\nu - E_g - E_p)^2}{1 - exp(-\frac{E_p}{k_B T})}$$

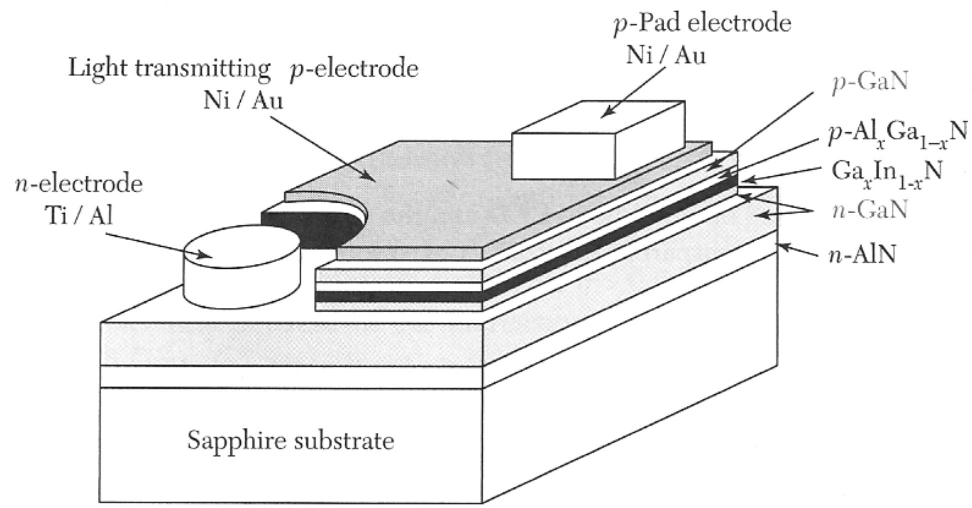


Light emitting diodes





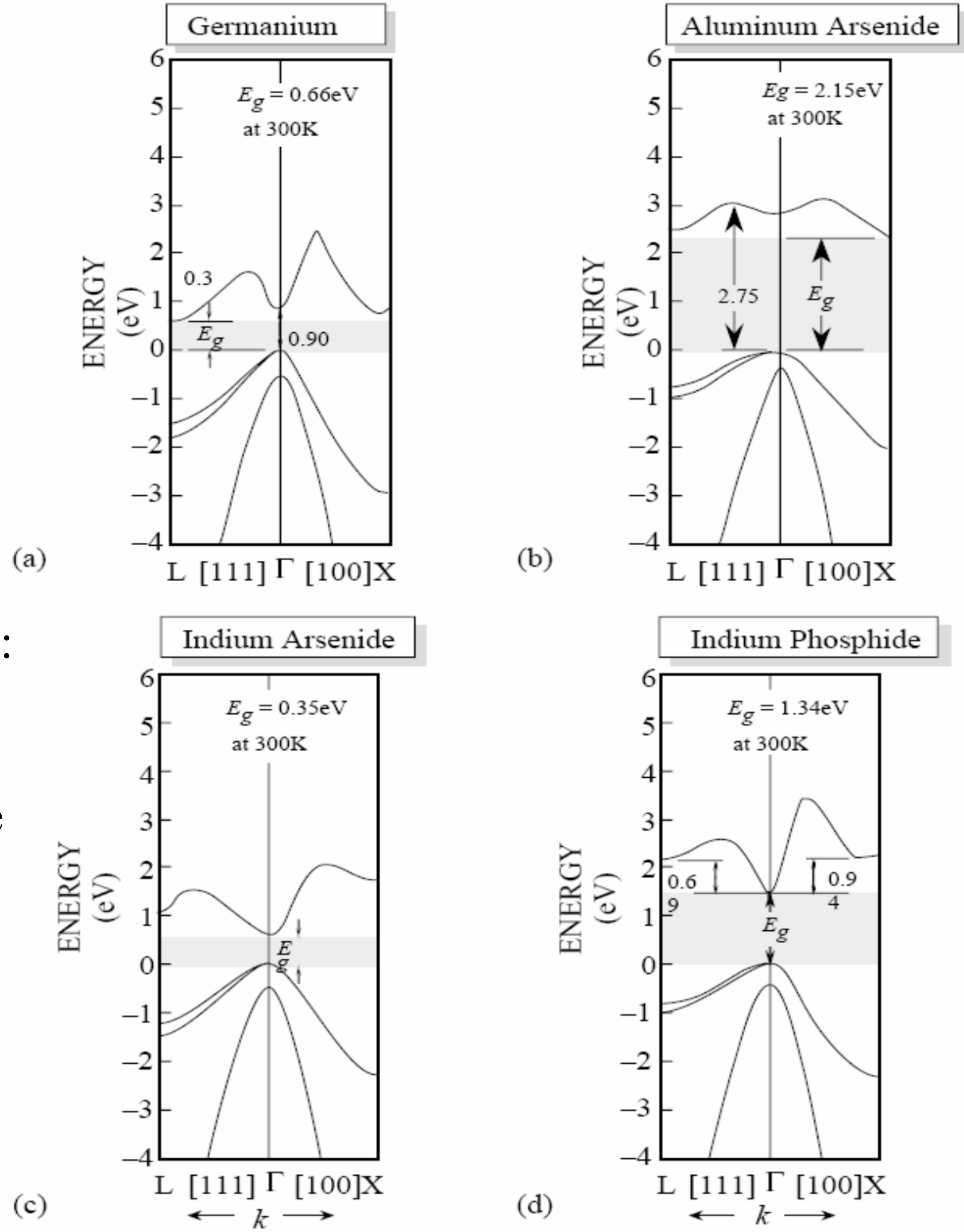




Solid state lighting is efficient.

direct bandgap:
$\Delta k = 0$

photons can be emitted



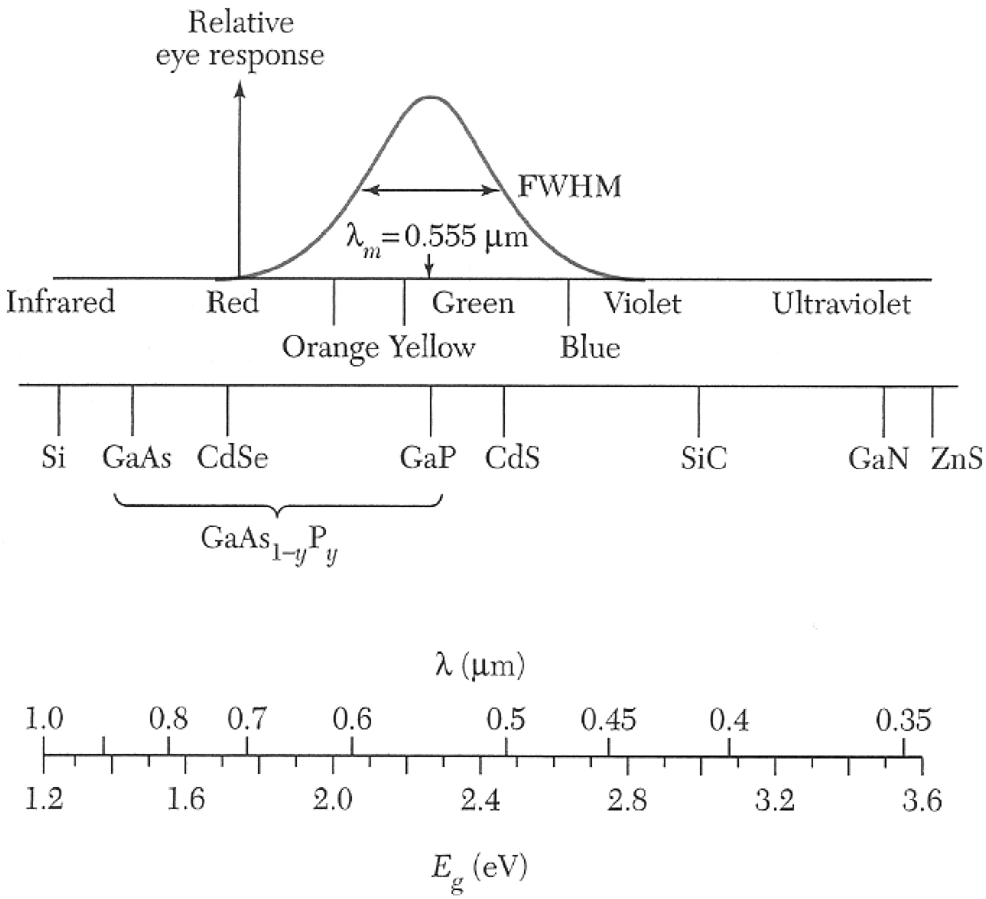
indirect bandgap:
$\Delta k \neq 0$

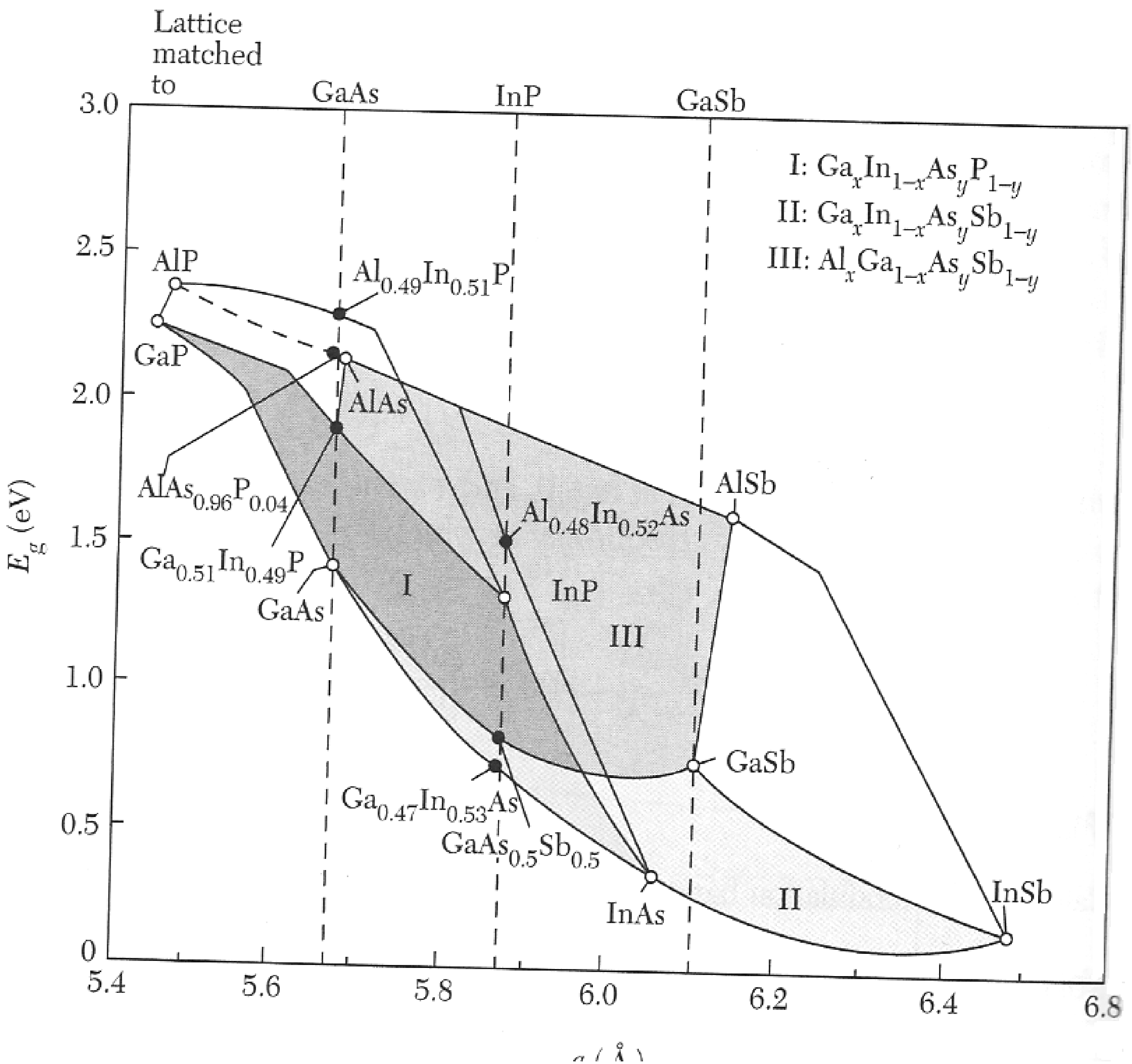
phonons are emitted

Light emitting diodes

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

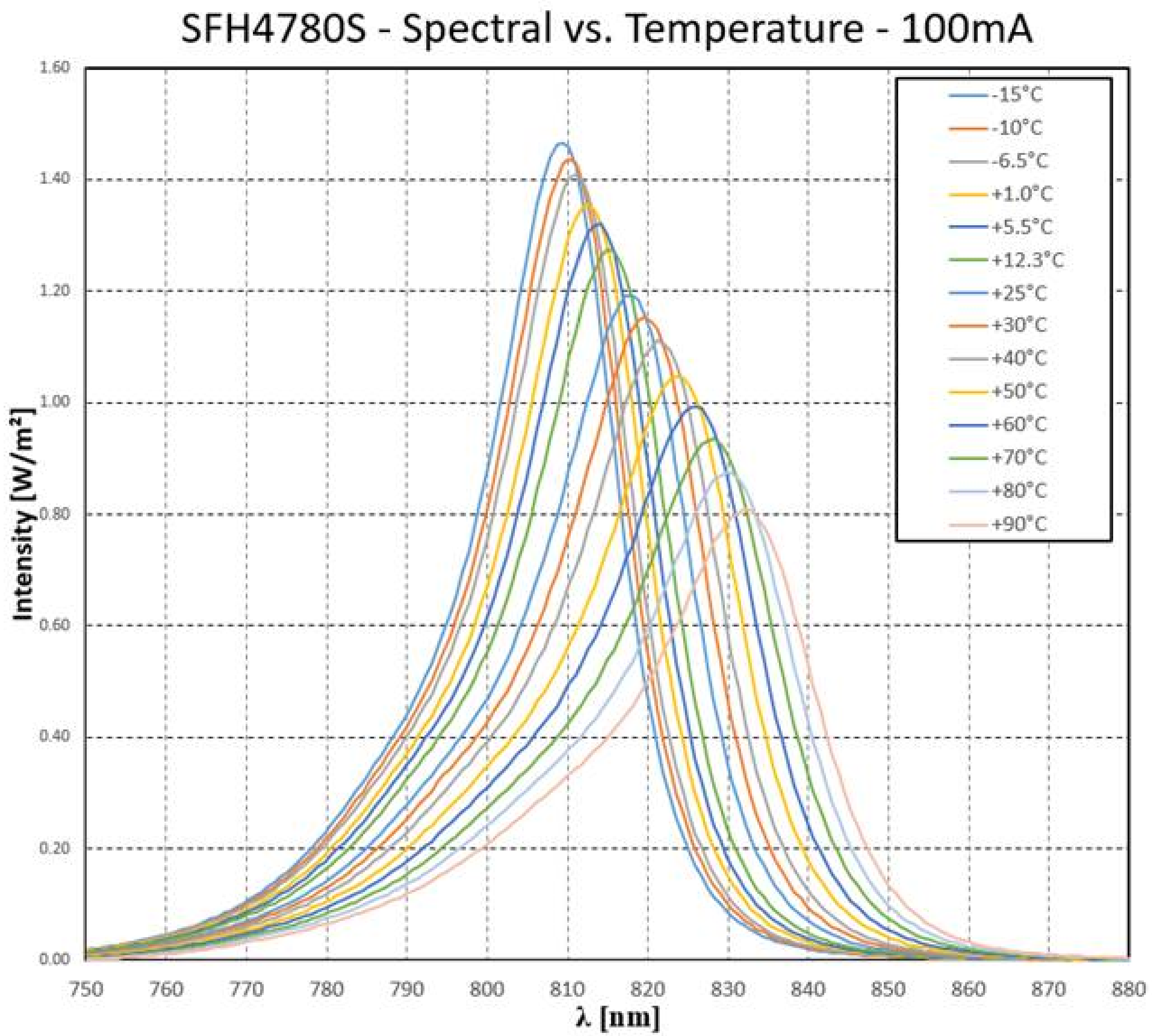
Material	Wavelength (nm)
InAsSbP/InAs	4200
InAs	3800
GaInAsP/GaSb	2000
GaSb	1800
$Ga_xIn_{1-x}As_{1-y}P_y$	1100-1600
$Ga_{0.47}In_{0.53}As$	1550
$Ga_{0.27}In_{0.73}As_{0.63}P_{0.37}$	1300
GaAs:Er,InP:Er	1540
Si:C	1300
GaAs:Yb,InP:Yb	1000
$Al_xGa_{1-x}As$:Si	650-940
GaAs:Si	940
$Al_{0.11}Ga_{0.89}As$:Si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





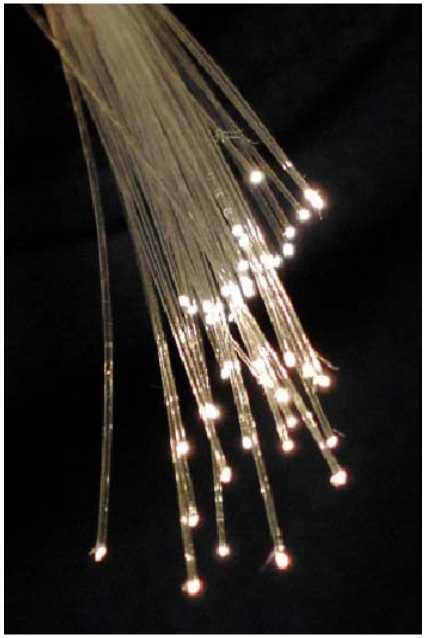
Lattice matched to
GaAs
InP
GaSb
I: $Ga_xIn_{1-x}As_yP_{1-y}$
II: $Ga_xIn_{1-x}As_ySb_{1-y}$
III: $Al_xGa_{1-x}As_ySb_{1-y}$
AlP
GaP
$Al_{0.49}In_{0.51}P$
AlAs
$AlAs_{0.96}P_{0.04}$
$Ga_{0.51}In_{0.49}P$
GaAs
AlSb
$Al_{0.48}In_{0.52}As$
InP
I
III
GaSb
$Ga_{0.47}In_{0.53}As$
$GaAs_{0.5}Sb_{0.5}$
InAs
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

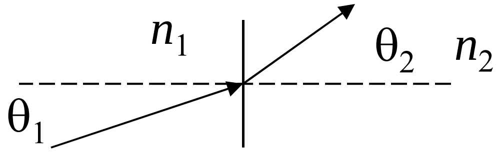
IR LED



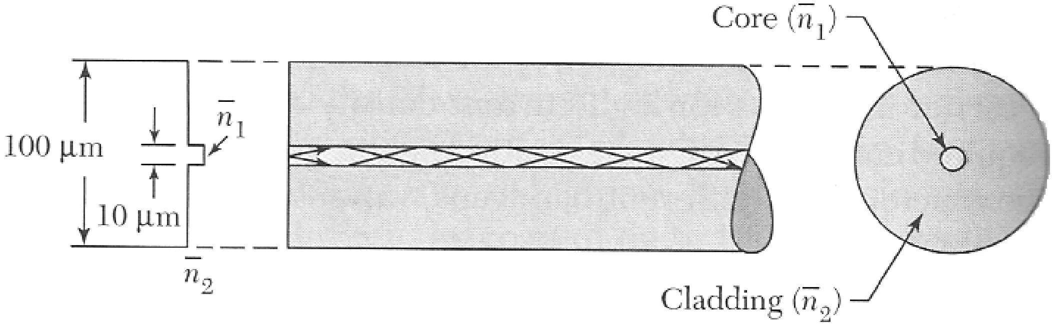
Measurement by Jan Enenkel

Confinement of light by total internal reflection

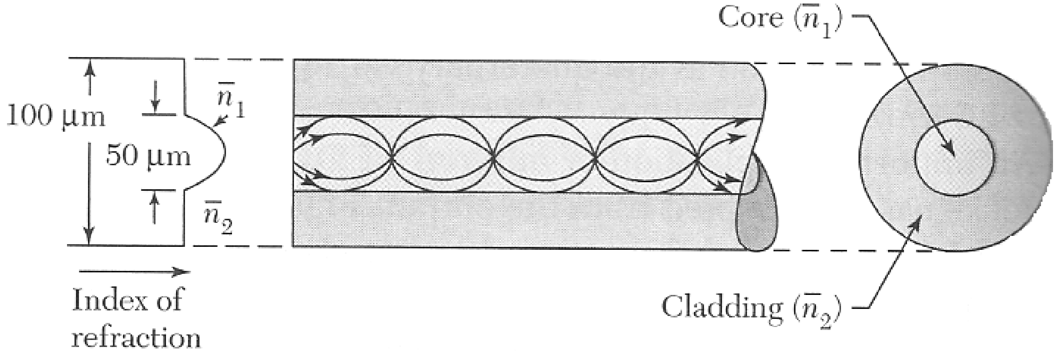




$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

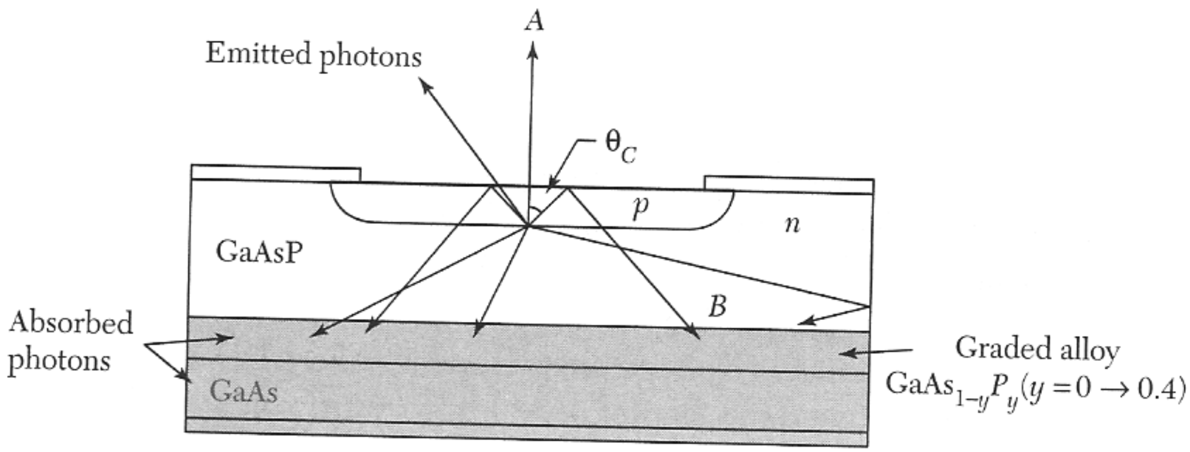


less pulse spreading for parabolically graded fiber

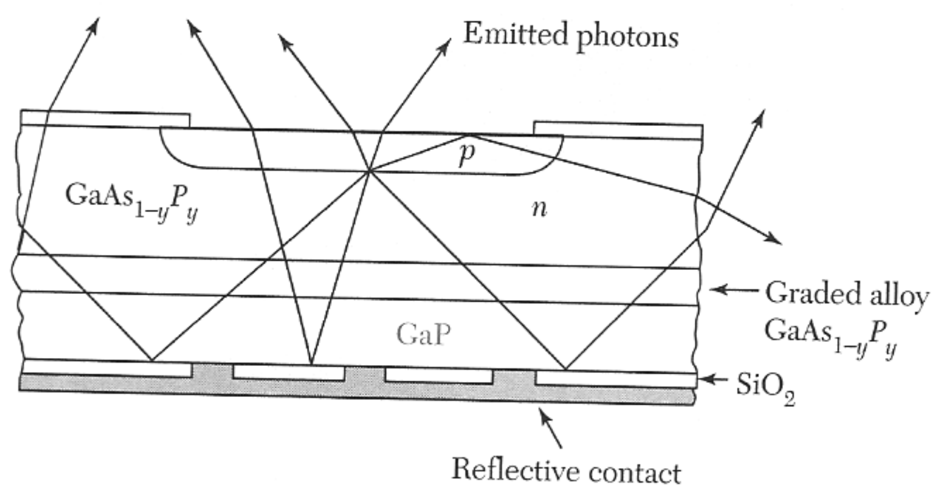


0.6 dB/km at 1.3 µm and 0.2 dB/km at 1.55 µm

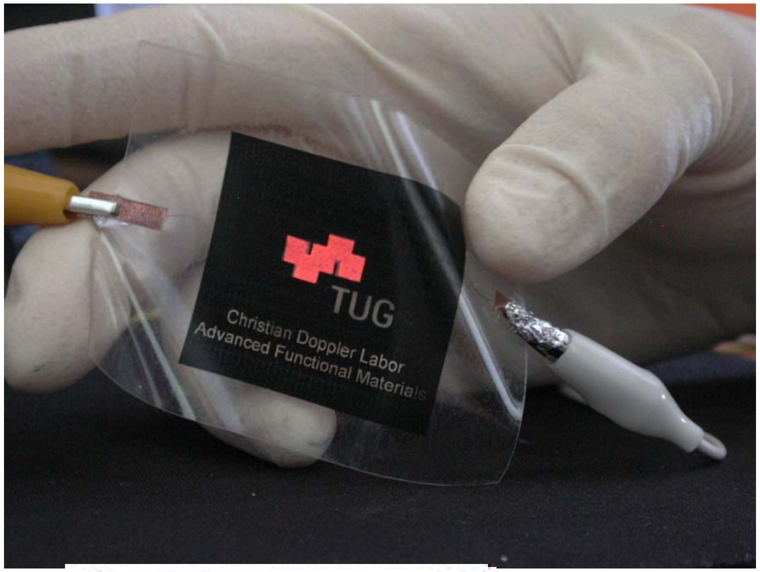
Light emitting diodes

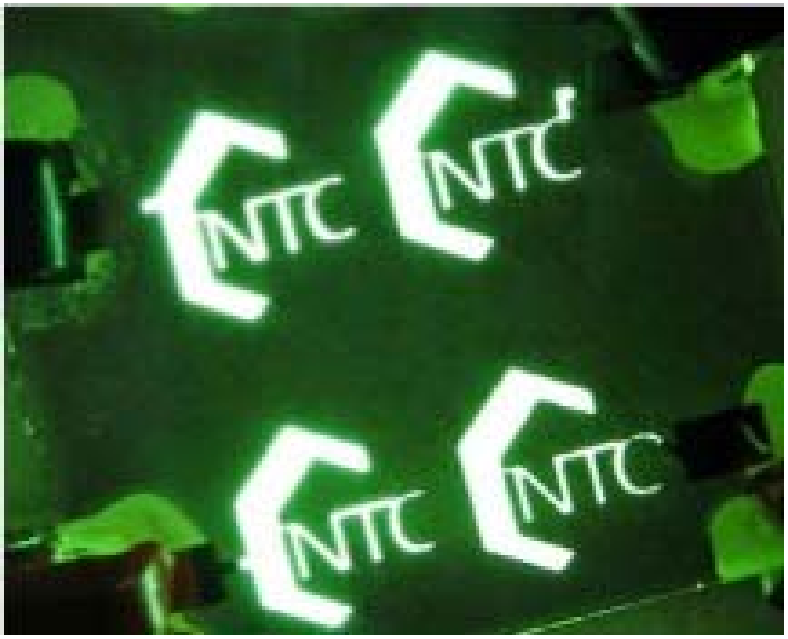


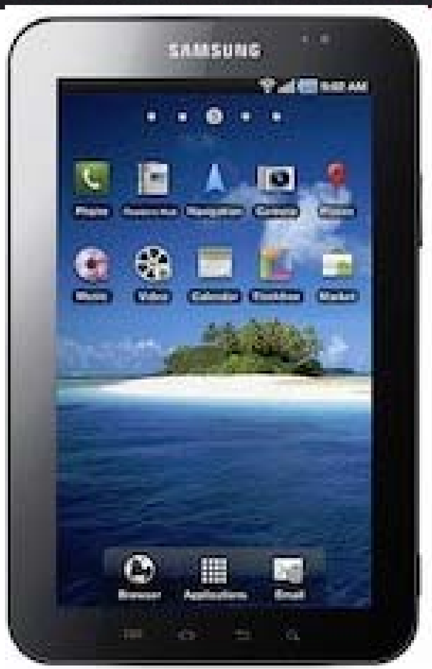
absorption
reflection
total internal reflection



OLEDs







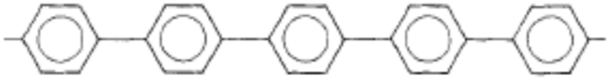
Galaxy Tab

Encapsulation technology

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).

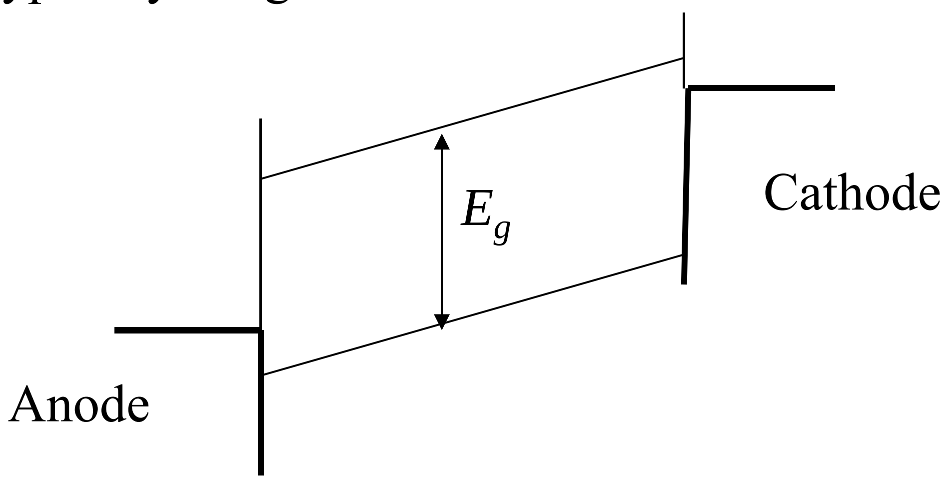


OLEDs

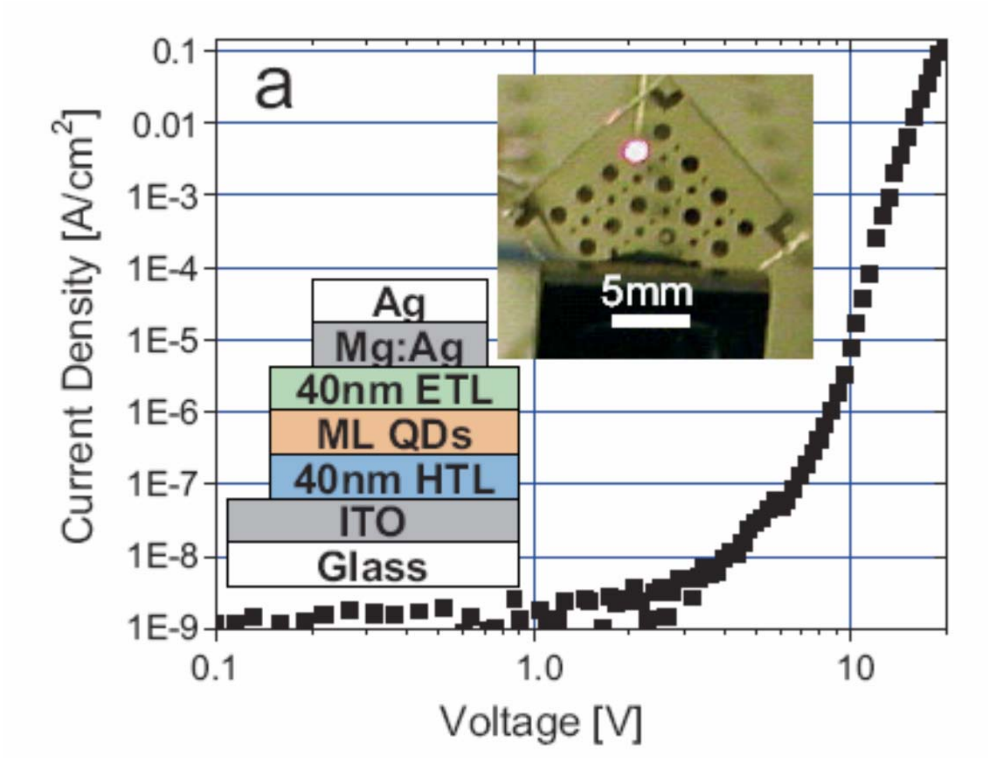
Aluminum cathode
Electron transport layer
Emission layer
Hole transport layer
ITO anode
Glass

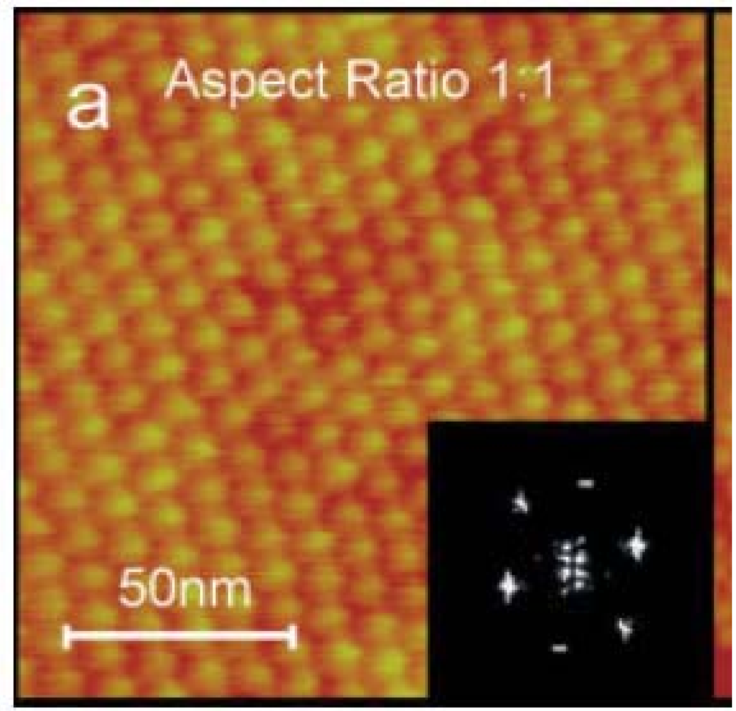
Cathode is typically a low work function material Al, Ca - injects electrons

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



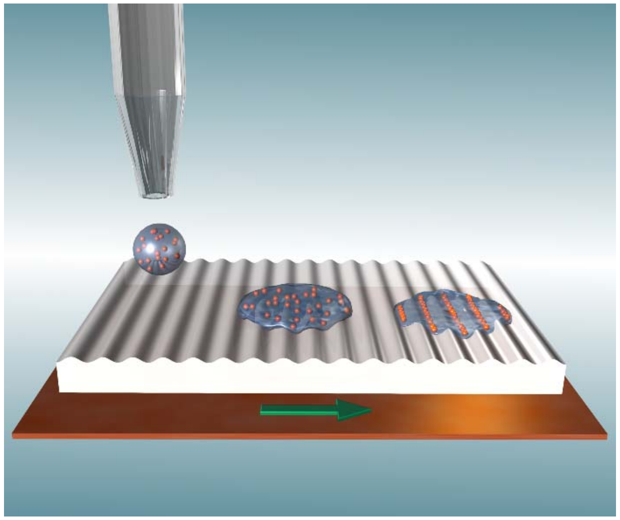
Q-dot LEDs

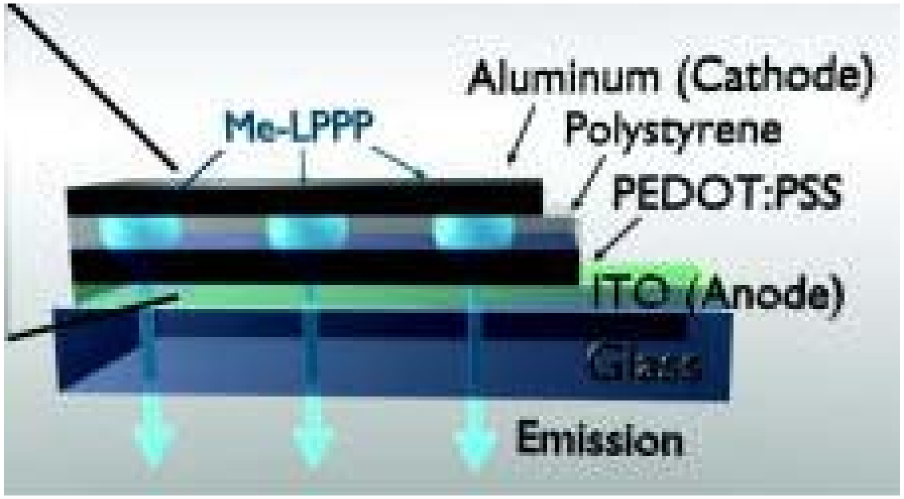




Coe-Sullivan, et al. Advanced Functional Materials,
10.1002/adfm.200400468

Nanoparticle OLEDs





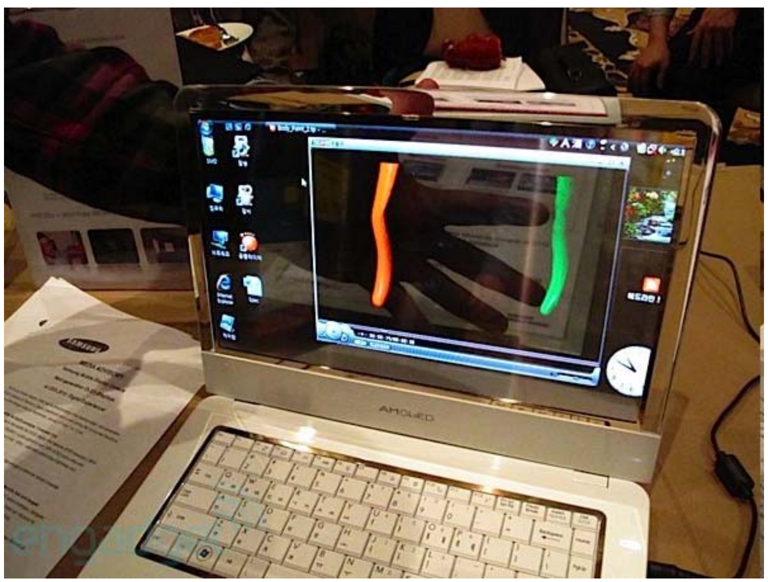
Semiconductor nanosphere (Me-LPPP) OLEDs

Appl. Phys. Lett. 92, 183305 (2008)

Efficient lighting

Very efficient
Many colors possible
No toxic chemicals

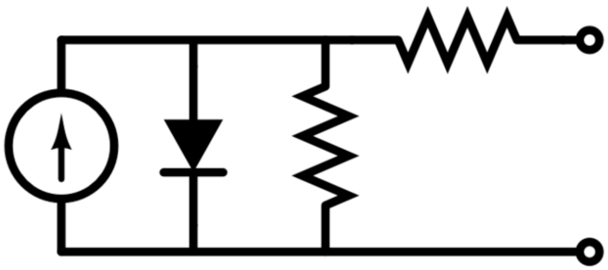
Flexible, transparent, wearable displays



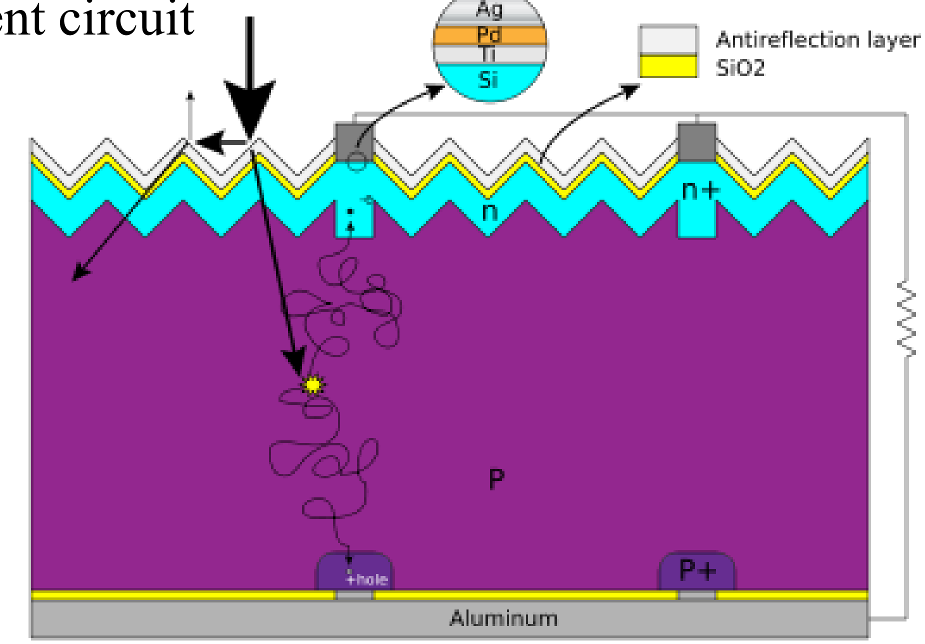
Transparent AMOLED

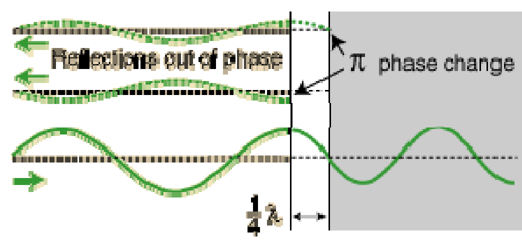
Folding display

Solar cell

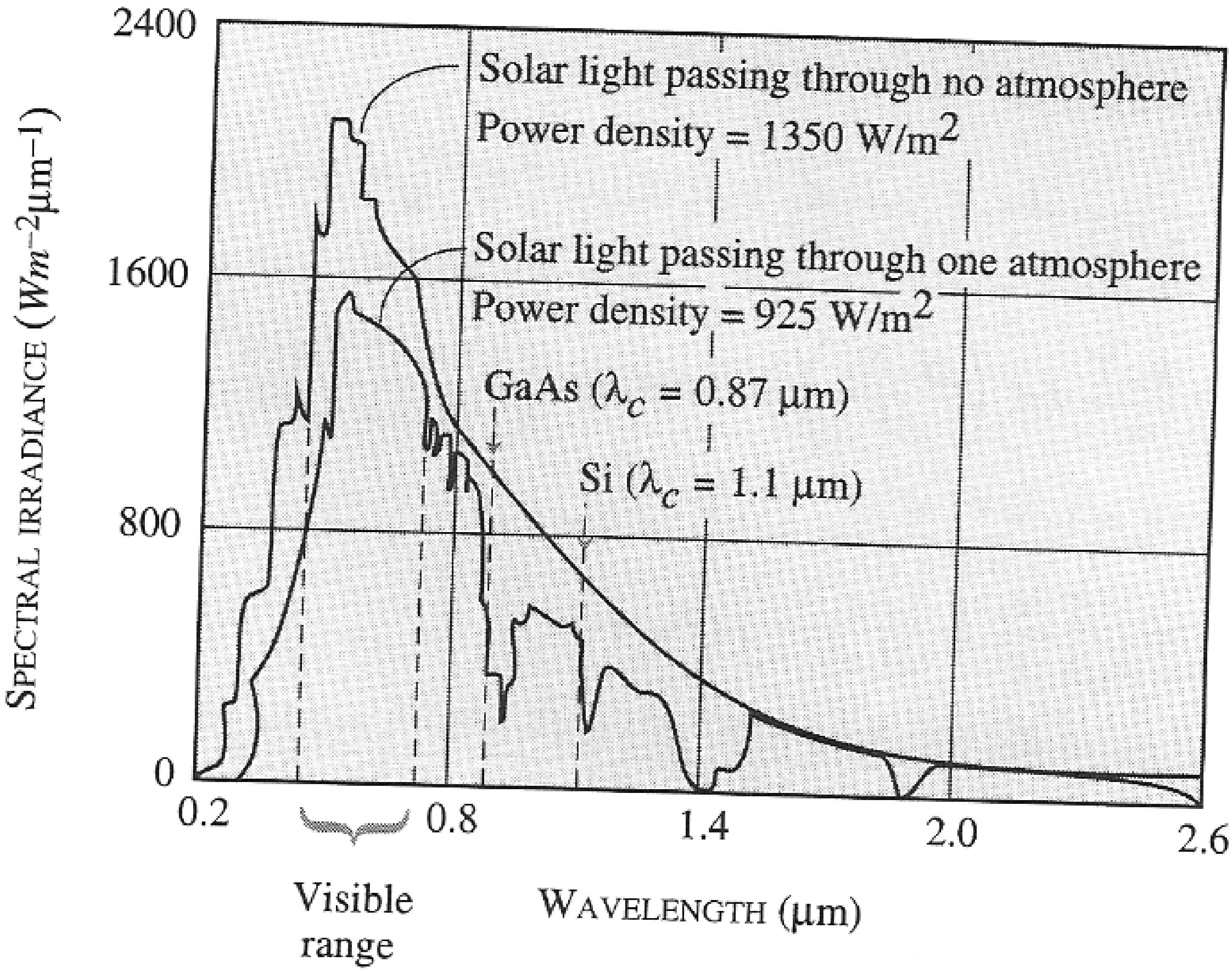


Equivalent circuit

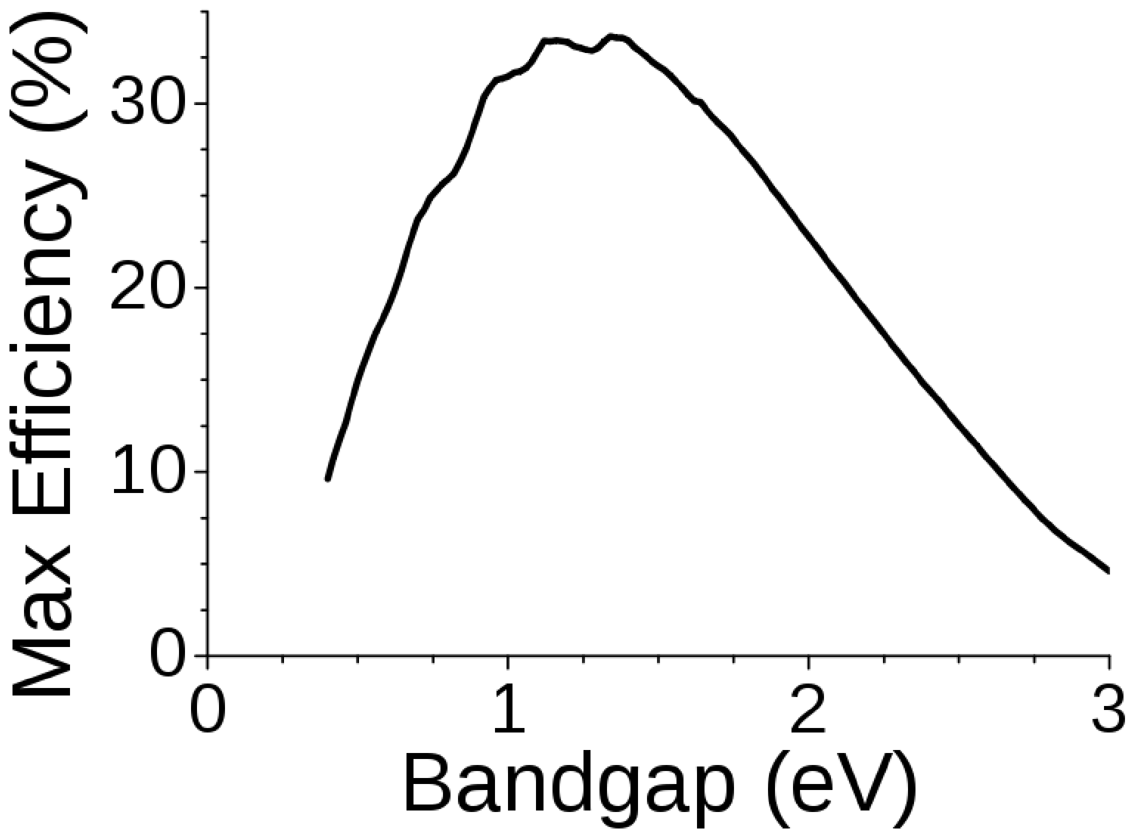




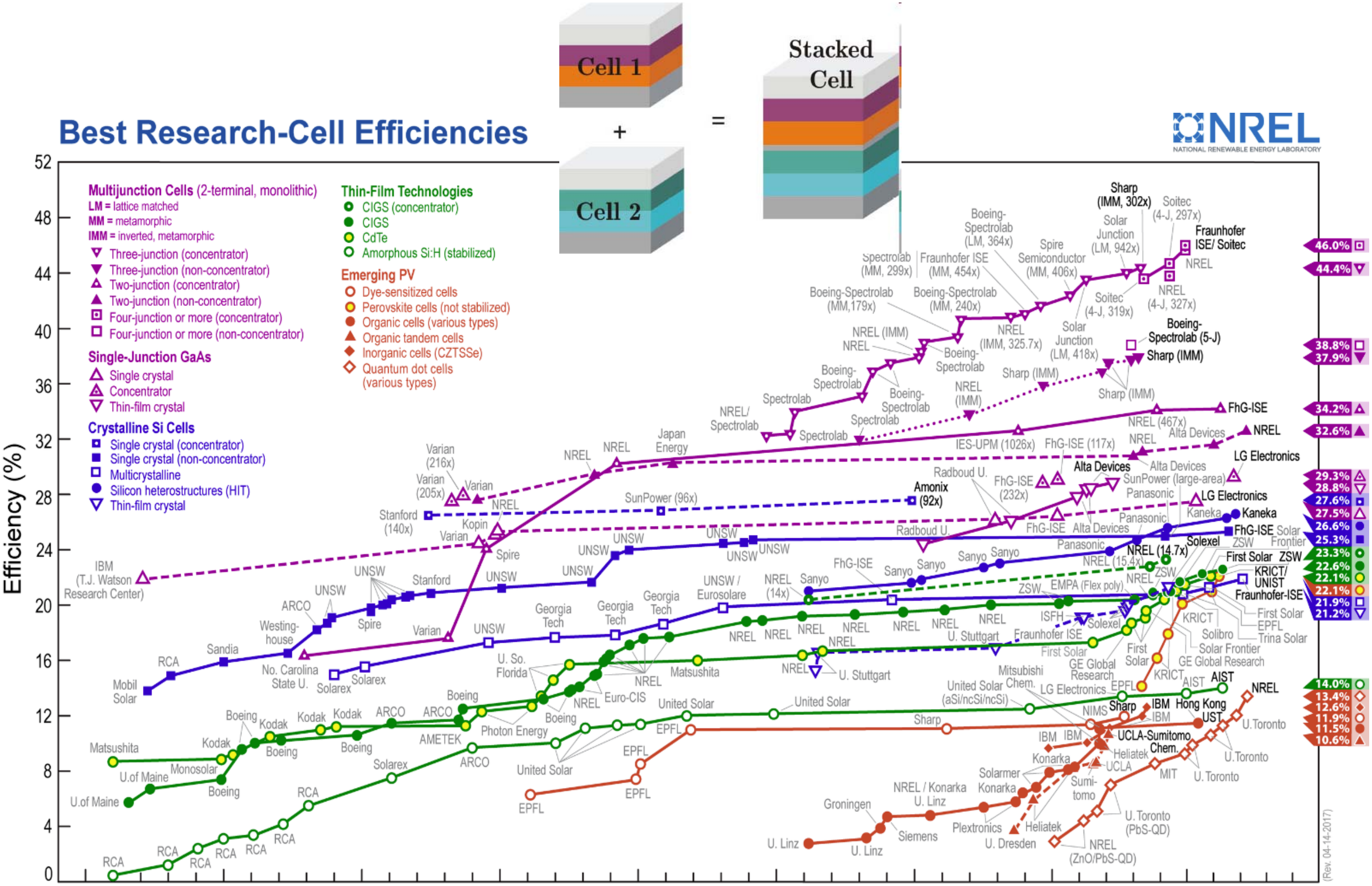
Solar spectrum



Shockley–Queisser limit



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



Biofuel efficiency ~ 1%