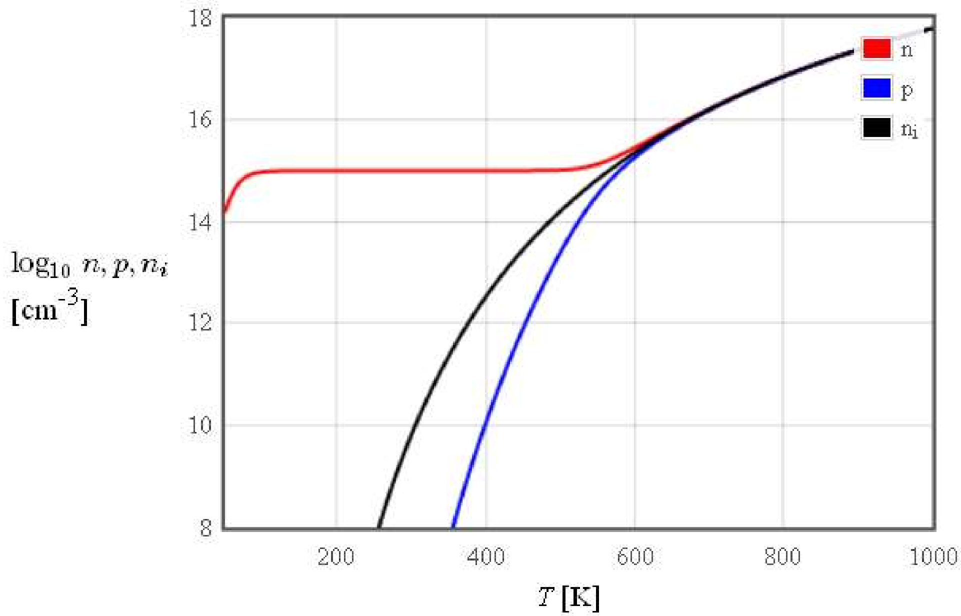
n-type

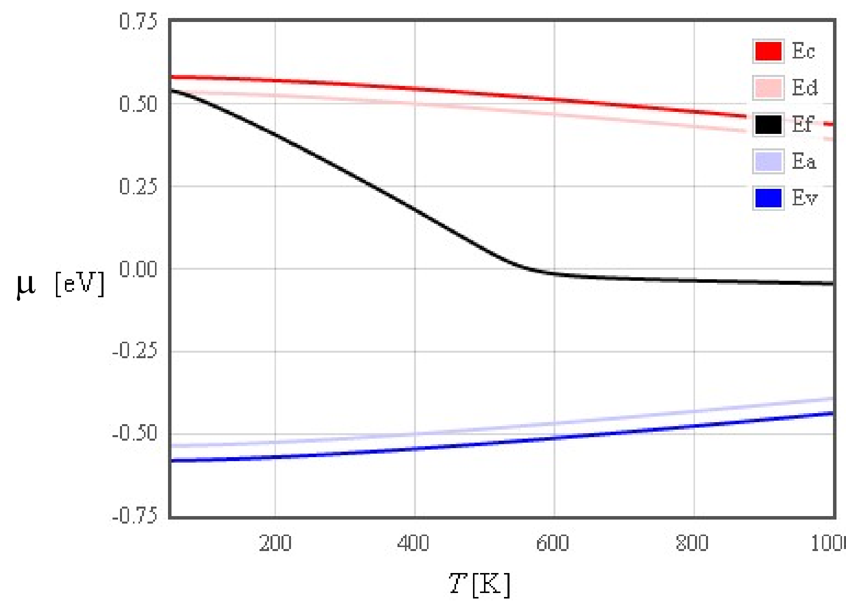
n-type $N_D > N_A$, $p \sim 0$

$$n = N_D = N_c \exp\left(\frac{\mu - E_c}{k_B T}\right)$$

$$\boxed{\mu = E_c - k_B T \ln\left(\frac{N_c}{N_D}\right)}$$

For n-type, $n \sim$ density of donors, $p = n_i^2/n$





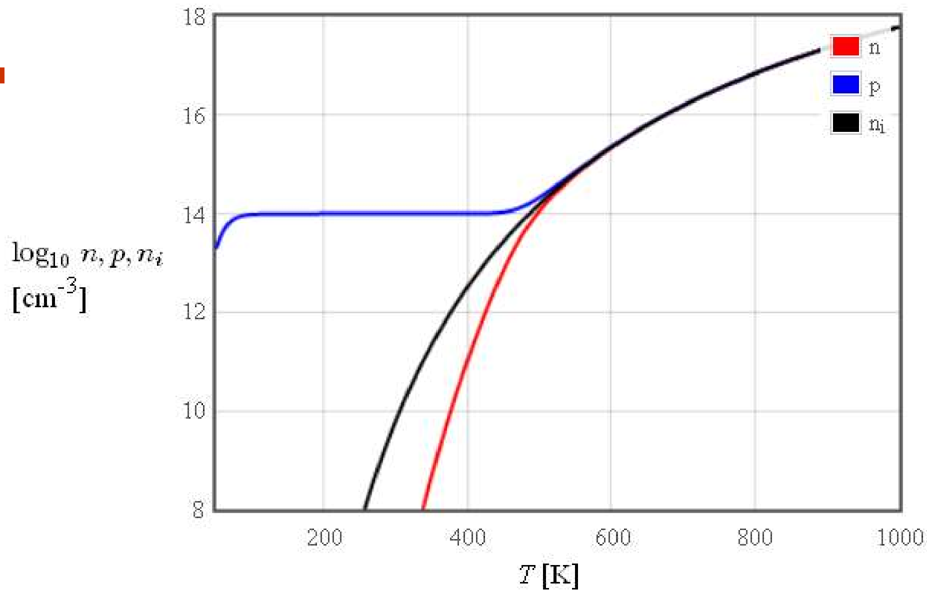
p-type

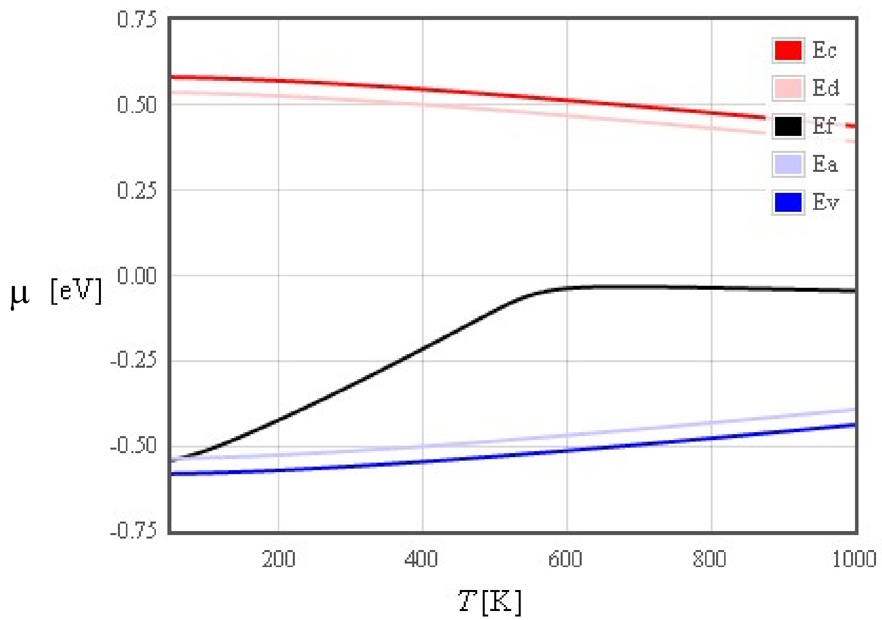
p-type $N_A > N_D$, $n \sim 0$

$$p = N_A = N_v \exp\left(\frac{E_v - \mu}{k_B T}\right)$$

$$\mu = E_v + k_B T \ln\left(\frac{N_v}{N_A}\right)$$

For p-type, $p \sim$ density of acceptors, $n = n_i^2/p$





Degenerate semiconductor

Heavily doped semiconductors are called degenerately doped

$N_D > 0.1\ N_c$ -> E_F in the conduction band

$N_A > 0.1\ N_v$ -> E_F in the valence band

Heavy doping narrows the band gap

The Boltzmann approximation is not valid

Degenerate semiconductors = metal

Ohm's law

For semiconductors:

$$\vec{v}_{d,e} = -\mu_e \vec{E} \qquad \vec{v}_{d,h} = \mu_h \vec{E}$$

μ_e = electron mobility

μ_h = hole mobility

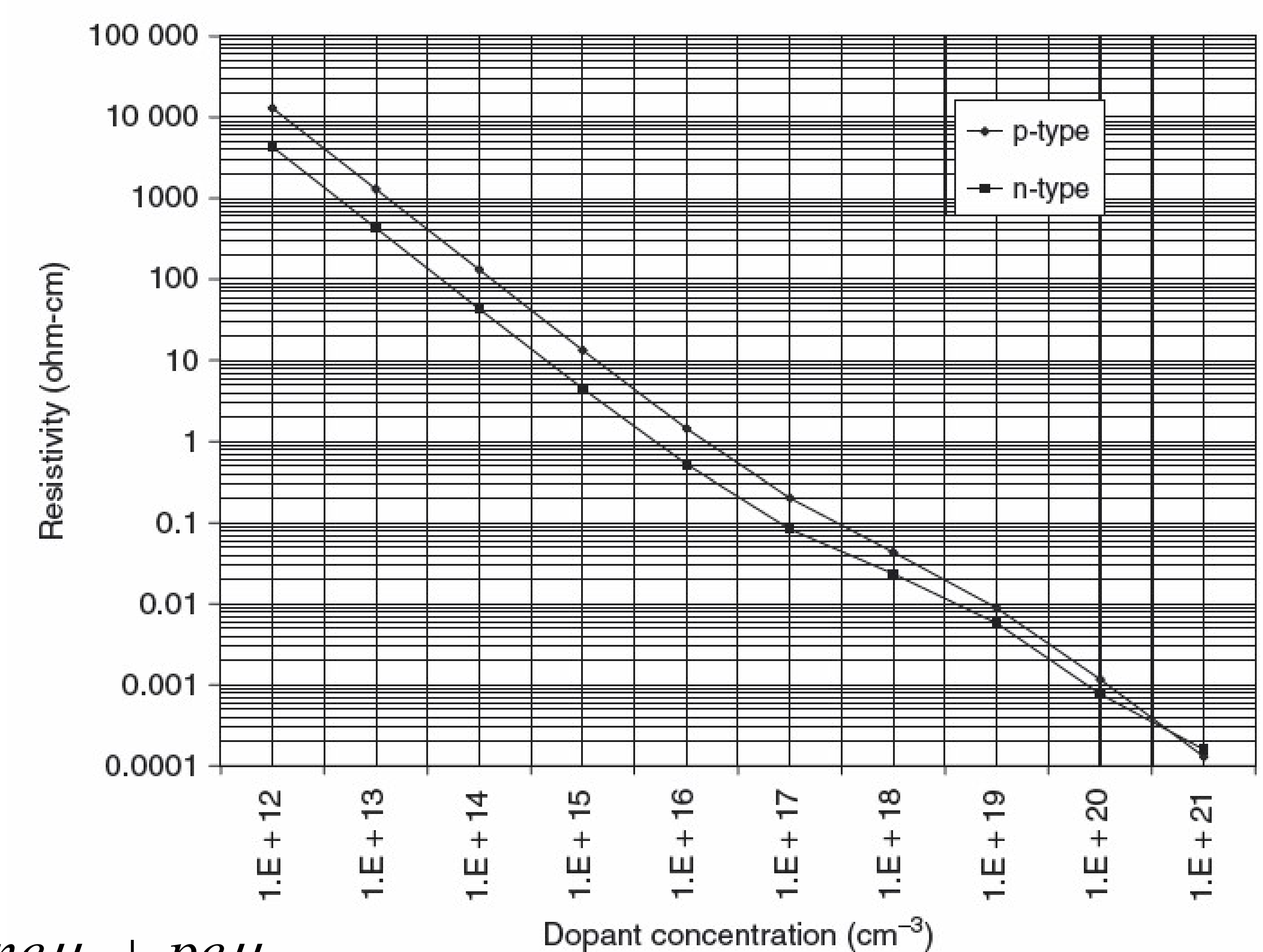
$$\vec{j} = -ne\vec{v}_{d,e} + pe\vec{v}_{d,h} = \left(\frac{ne^2 \tau_{sc,e}}{m_e^*} + \frac{pe^2 \tau_{sc,h}}{m_h^*} \right) \vec{E}$$

$$\sigma = \frac{ne^2 \tau_{sc,e}}{m_e^*} + \frac{pe^2 \tau_{sc,h}}{m_h^*}$$

Conductivity of intrinsic silicon depends exponentially on temperature.
The conductivity of a doped semiconductor is constant for a range of T.

	Mobility at 300 K $(cm^2/V \cdot s)$	
Semiconductor	Electrons	Holes
C	800	1200
Ge	3900	1900
Si	1500	450
α-SiC	400	50
GaSb	5000	850
GaAs	8500	400
GaP	110	75
InAs	33000	460
InP	4600	150
CdTe	1050	100

Silicon

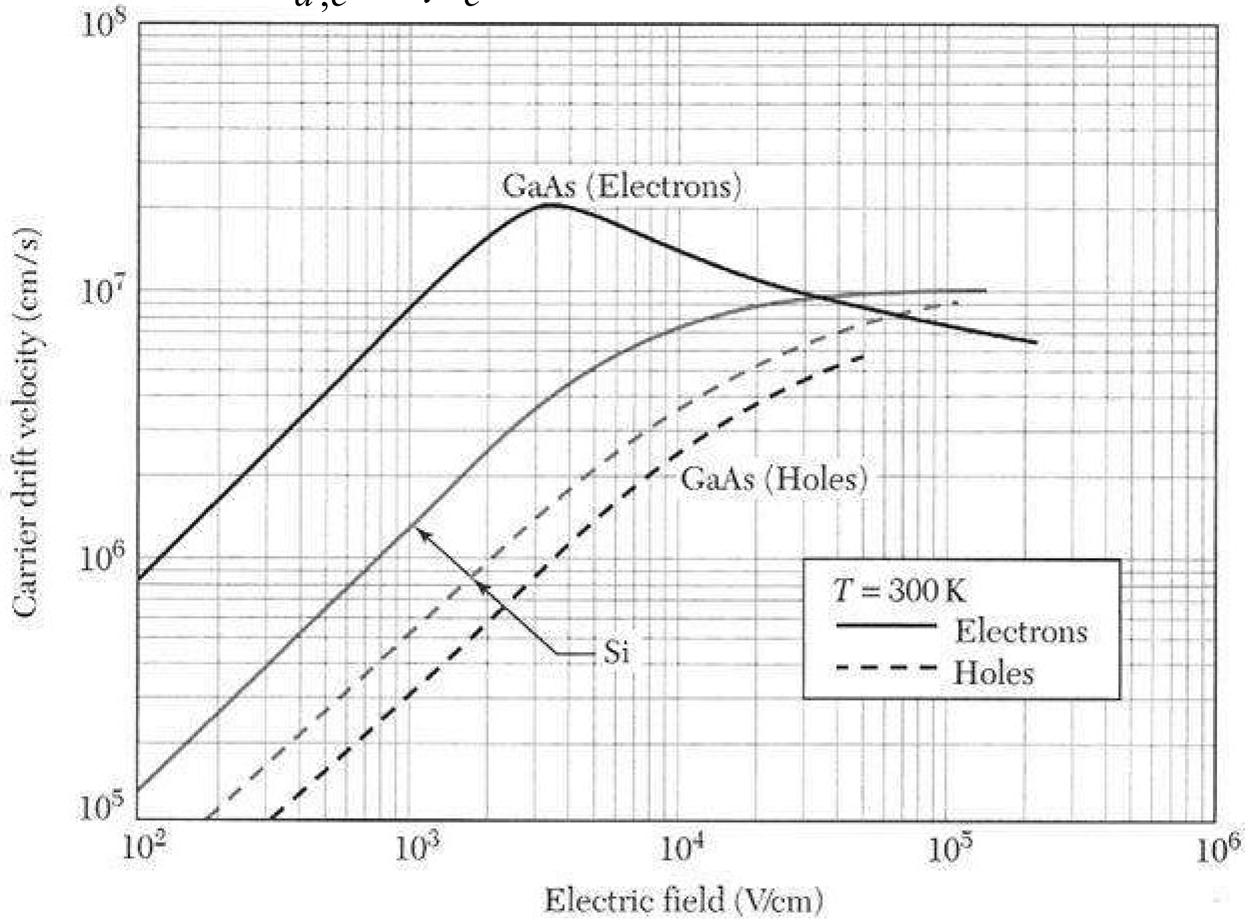


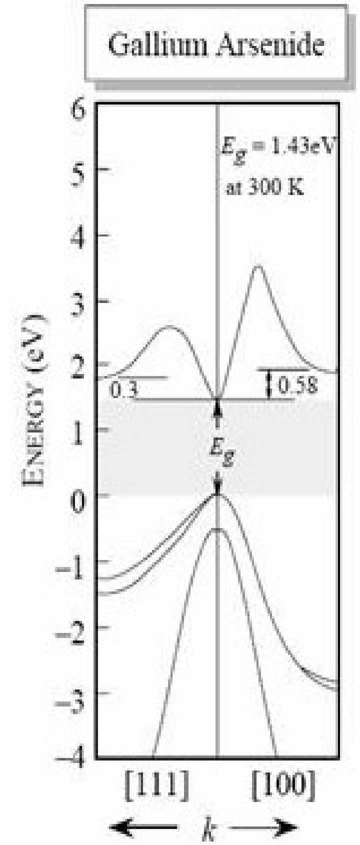
$$\frac{1}{\rho} = ne\mu_n + pe\mu_p$$

Franssila, Introduction to Microfabrication

High fields

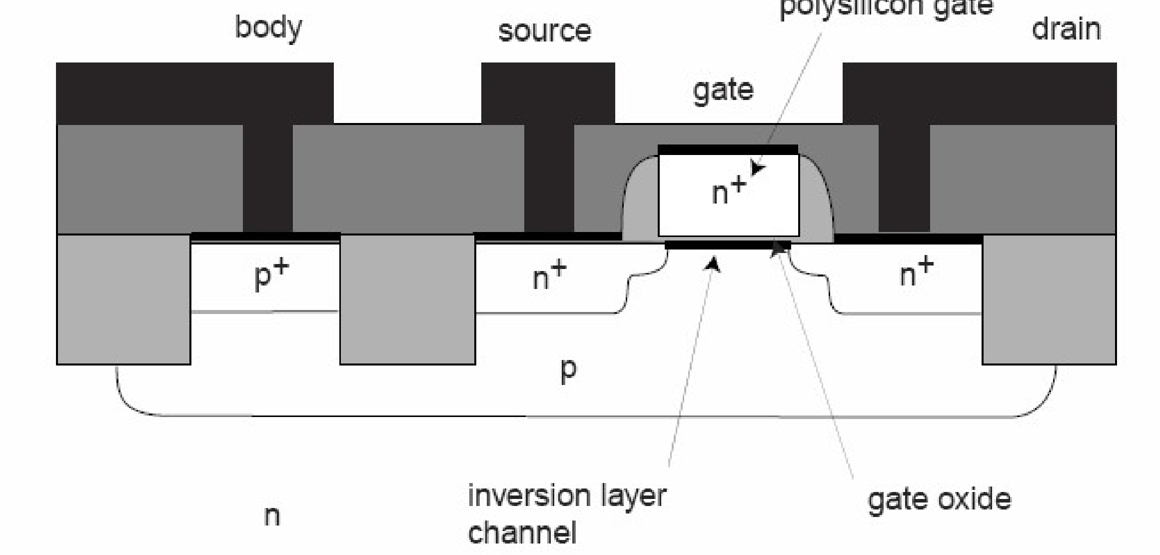
$$\vec{v}_{d,e} = \mu_e \vec{E} \qquad \vec{v}_{d,h} = \mu_h \vec{E}$$



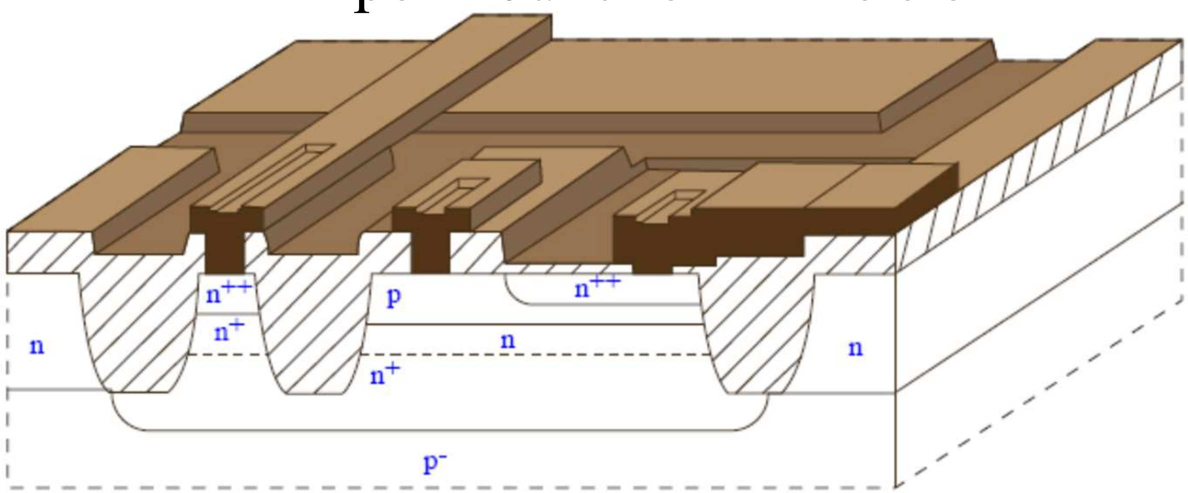


Emission of optical phonons causes the saturation of electron velocity.
There are no semiconductors without optical phonons.

MOSFET



Bipolar Junction Transistor



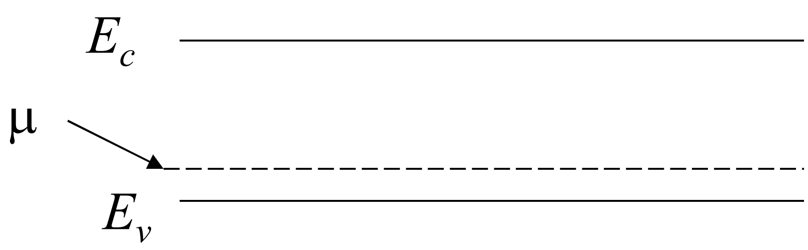
Oxide isolated integrated BJT - a modern process

pn junction

under normal operation conditions

p-type

$N_A > N_D \qquad p = N_A - N_D$

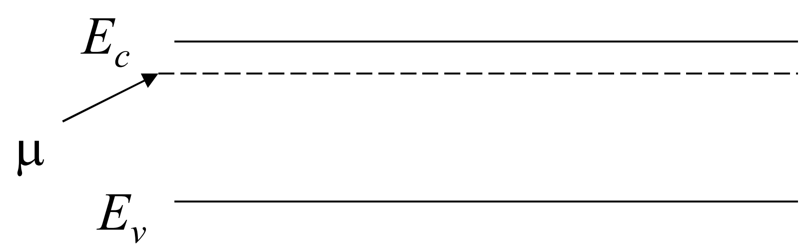


$$n = \frac{n_i^2}{p} = \frac{n_i^2}{N_A - N_D}$$

$$\mu = E_v + k_B T \ln\left(\frac{N_v}{N_A - N_D}\right)$$

n-type

$N_D > N_A \qquad n = N_D - N_A$

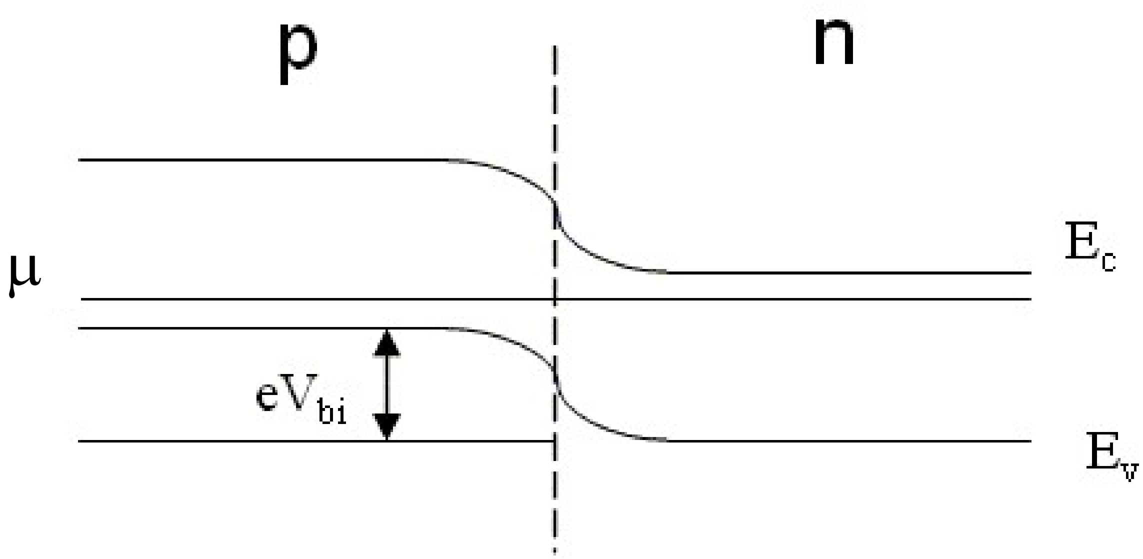


$$p = \frac{n_i^2}{n} = \frac{n_i^2}{N_D - N_A}$$

$$\mu = E_c - k_B T \ln\left(\frac{N_c}{N_D - N_A}\right)$$

Semiconductor devices   Kittel p. 503 - 512

V_{bi} built-in voltage



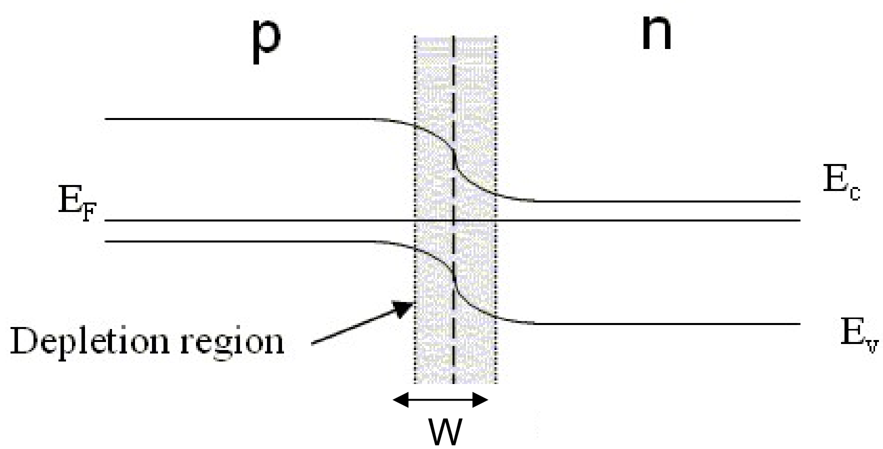
law of mass action

$$n_i^2 = N_c N_v \exp\left(\frac{-E_g}{k_B T}\right)$$

$$eV_{bi} = E_v + E_g - k_B T \ln\left(\frac{N_c}{N_D}\right) - E_v - k_B T \ln\left(\frac{N_v}{N_A}\right)$$

$$eV_{bi} = E_g - k_B T \ln\left(\frac{N_c N_v}{N_D N_A}\right) = k_B T \ln\left(\frac{N_D N_A}{n_i^2}\right)$$

Depletion width



$V_{bi} \sim 1$ V

$W \sim 1$ μm

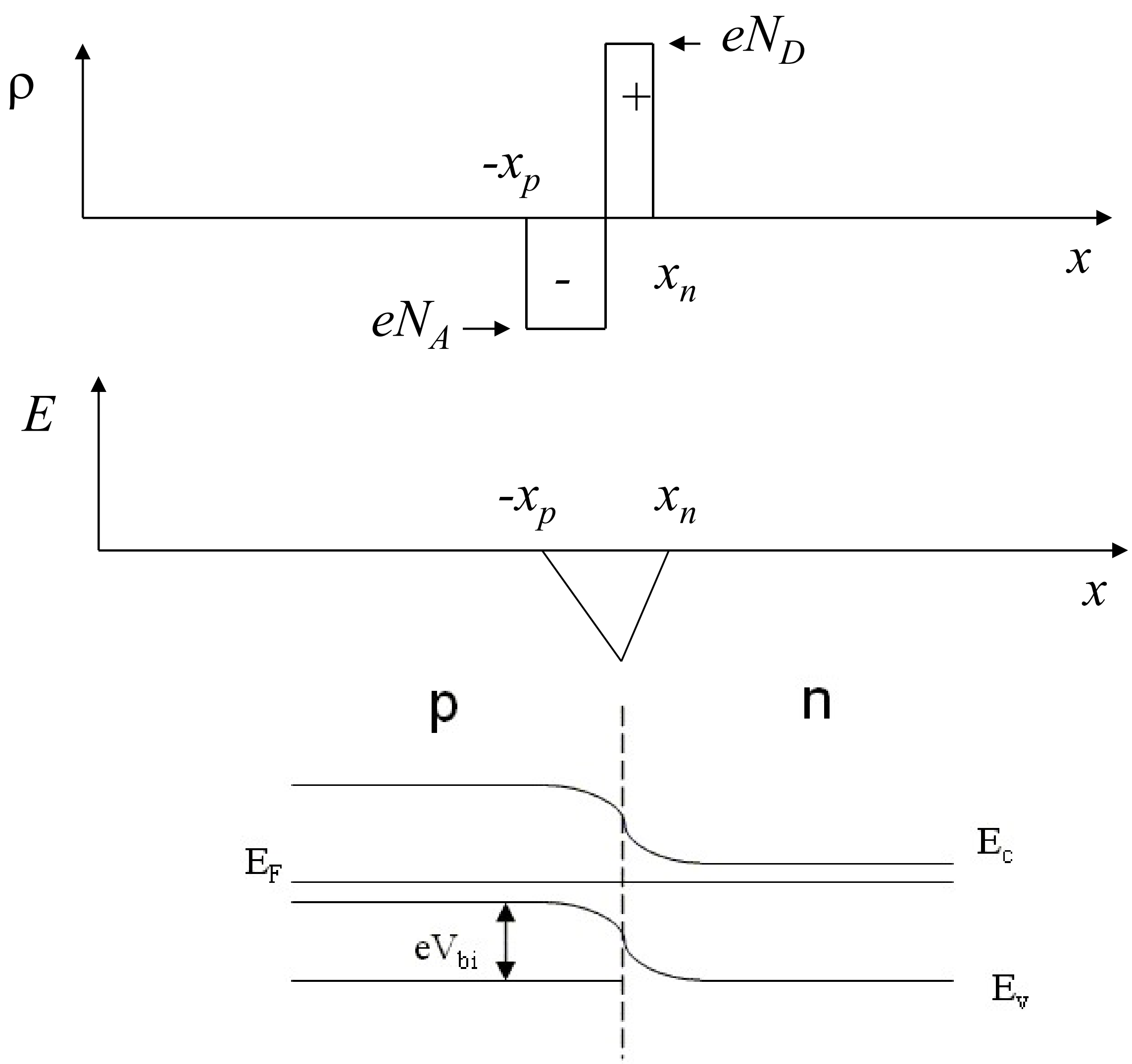
$E_{max} \sim 10^4$ V/cm

The electric field pushes the electrons towards the n-region and the holes towards the p-region.

Diffusion sends electrons towards the p-region and holes towards the n-region.

$$n = N_c \exp\left(\frac{\mu - E_c}{k_B T}\right) \qquad p = N_v \exp\left(\frac{E_v - \mu}{k_B T}\right)$$

depletion approximation



$$eV_{bi} = k_B T \ln\left(\frac{N_D N_A}{n_i^2}\right)$$

$$E = -\frac{eN_A}{\varepsilon}\left(x + x_p\right) \qquad -x_p > x > 0$$

$$E = \frac{eN_D}{\varepsilon}\left(x - x_n\right) \qquad 0 > x > x_n$$

$$V = \frac{eN_A}{\varepsilon}\left(\frac{x^2}{2} + xx_p\right) \qquad -x_p > x > 0$$

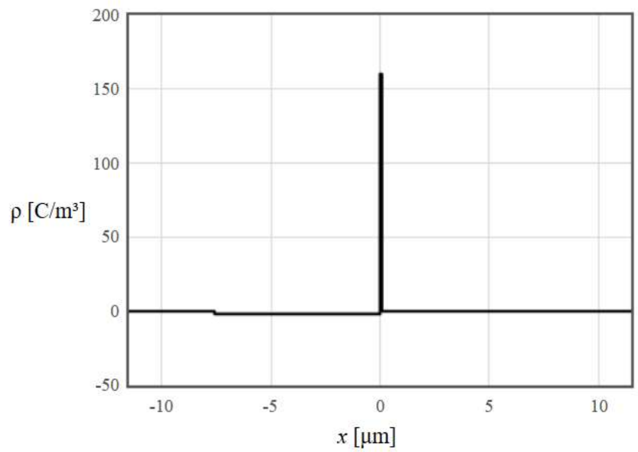
$$V = \frac{-eN_D}{\varepsilon}\left(\frac{x^2}{2} - xx_n\right) \qquad 0 > x > x_n$$

Abrupt pn junctions in the depletion approximation

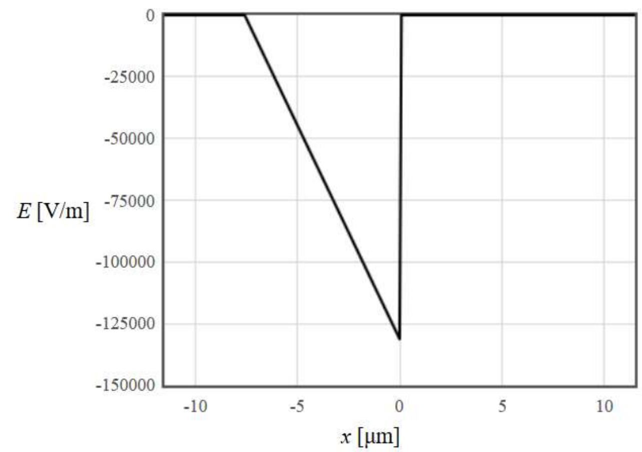
In an abrupt pn junction, the doping changes abruptly from p to n. It is common to solve for the band bending, the local electric field, the carrier concentration profiles, and the local conductivity in the d this approximation it is assumed that there is a depletion width W around the transition from p to n where the charge carrier densities are negligible. Outside the depletion width the charge carrier densiti densities so that the semiconductor is electrically neutral outside the depletion width. Using this approximation it is possible to calculate the important properties of the pn junction.

N_A = 1.15E13 1/cm³ N_D = 1E15 1/cm³ T = 300 K Start

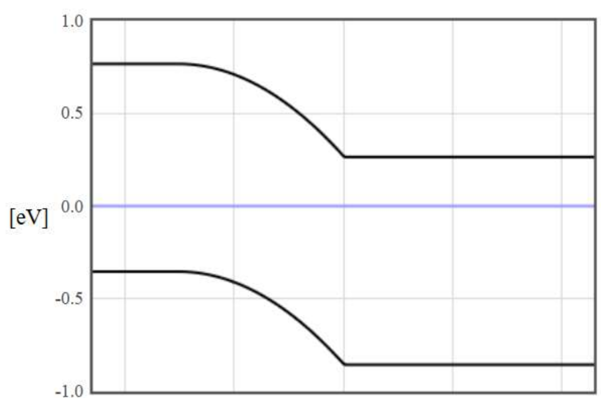
Charge density



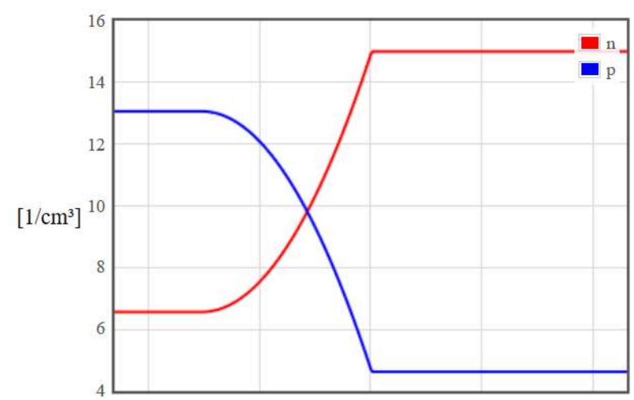
Electric field



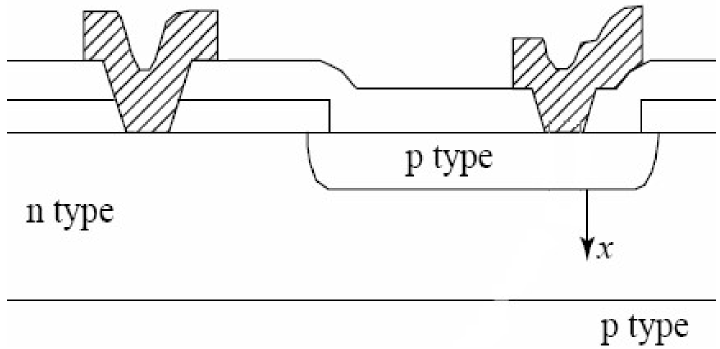
Band diagram



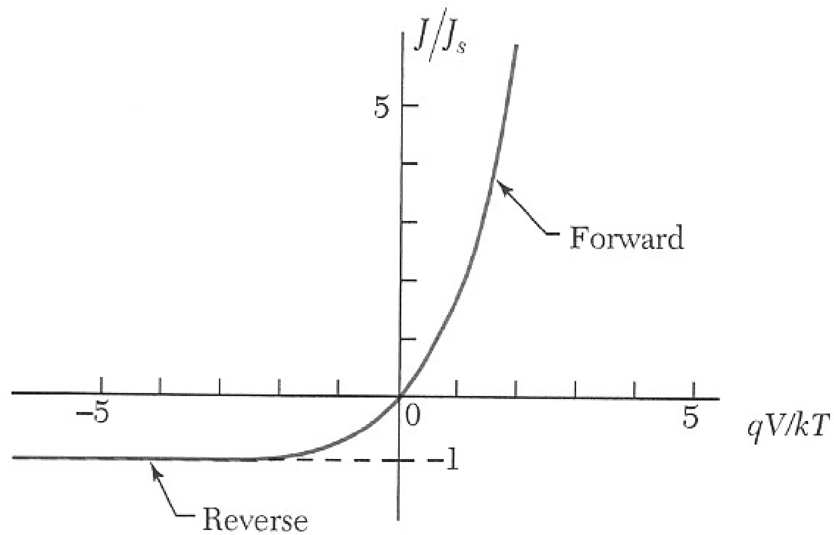
log(Carrier densities)



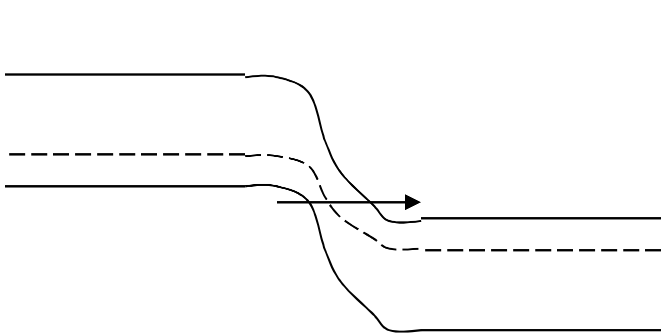
Diode



$$I = I_s\left(\exp\left(\frac{eV}{k_B T}\right) - 1\right)$$

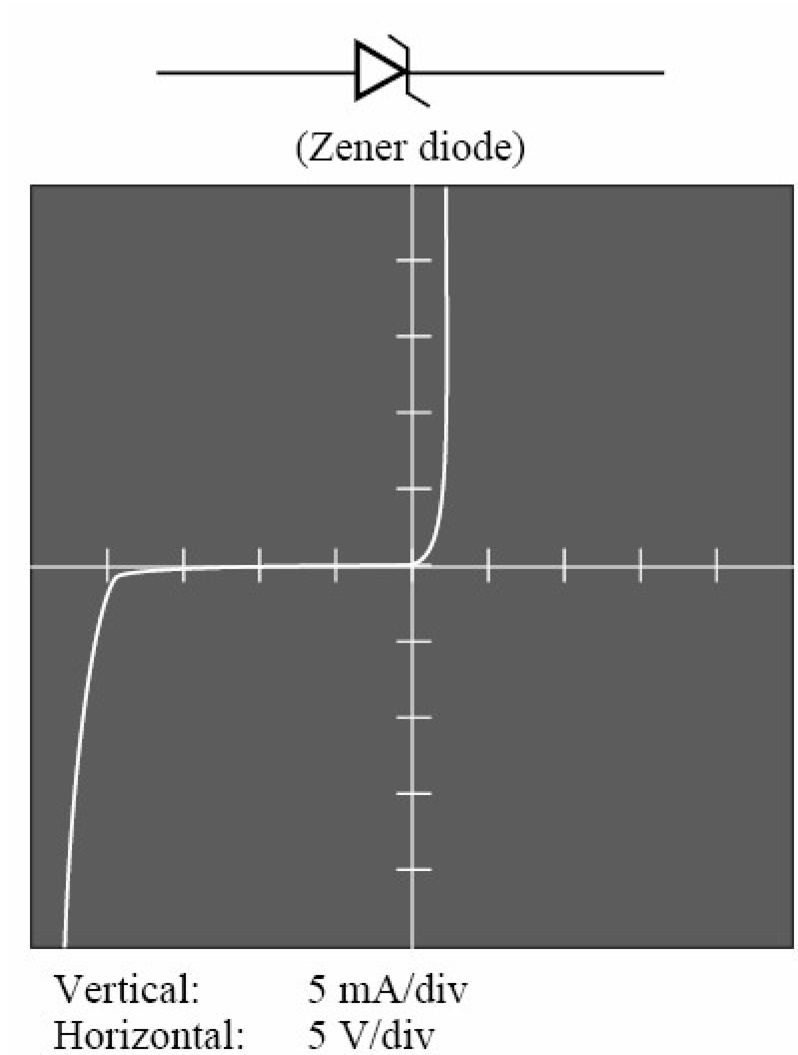


Zener tunneling

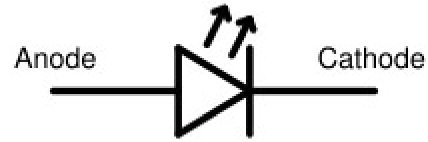


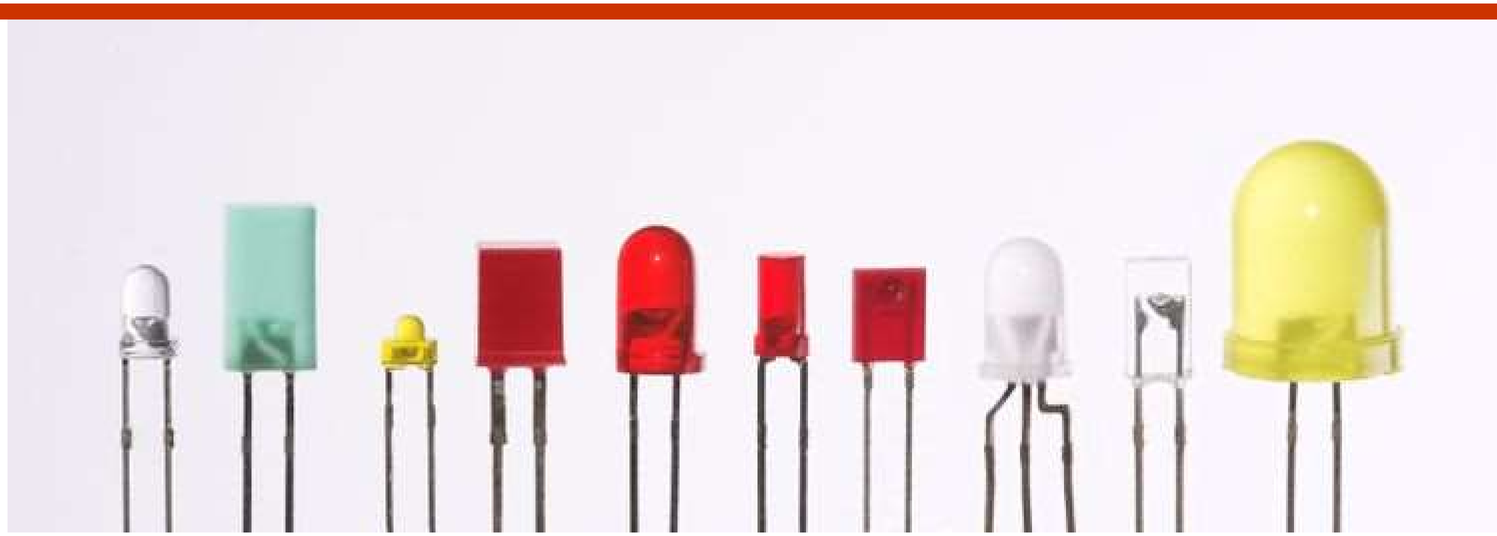
Electrons tunnel from valence band to conduction band

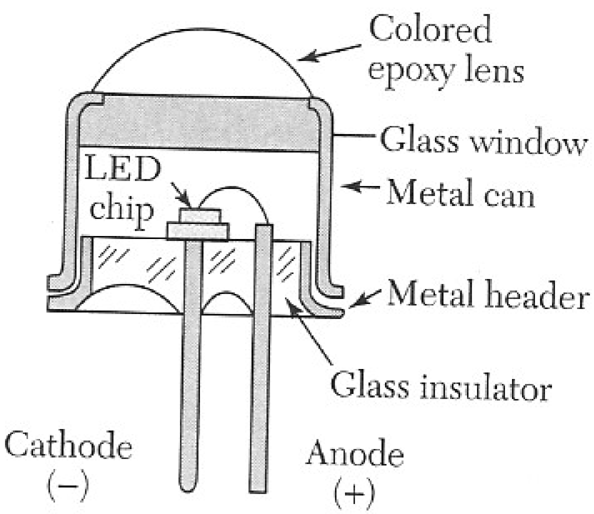
Occurs at high doping

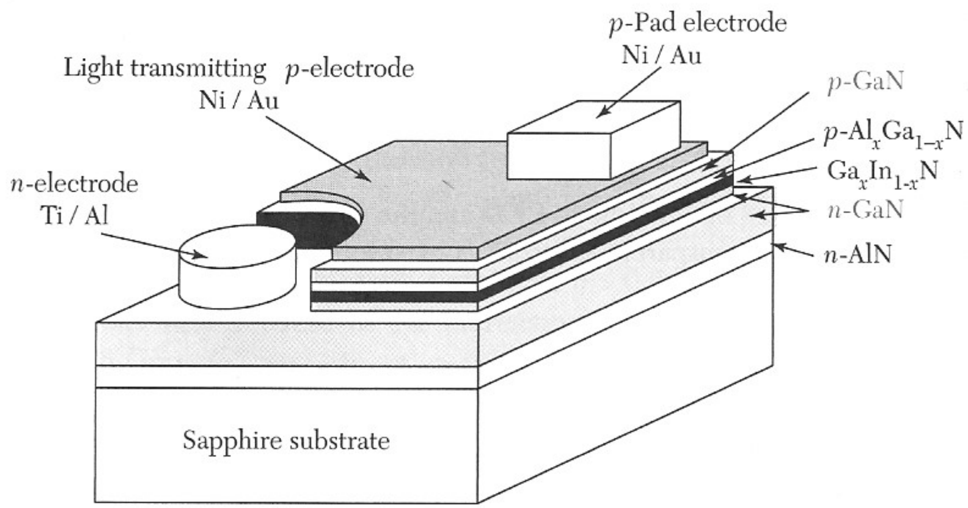


Light emitting diodes



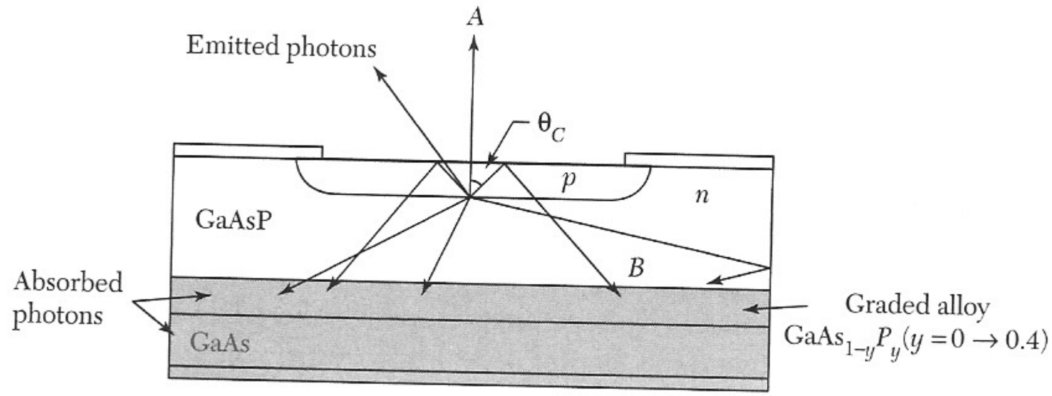




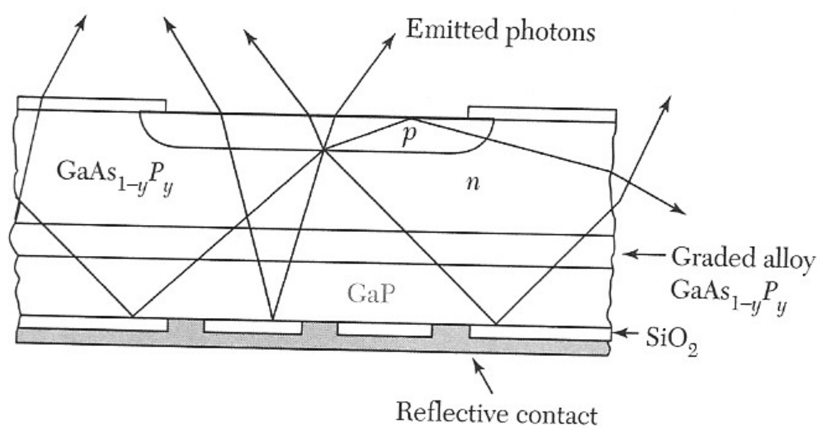


Solid state lighting is efficient.

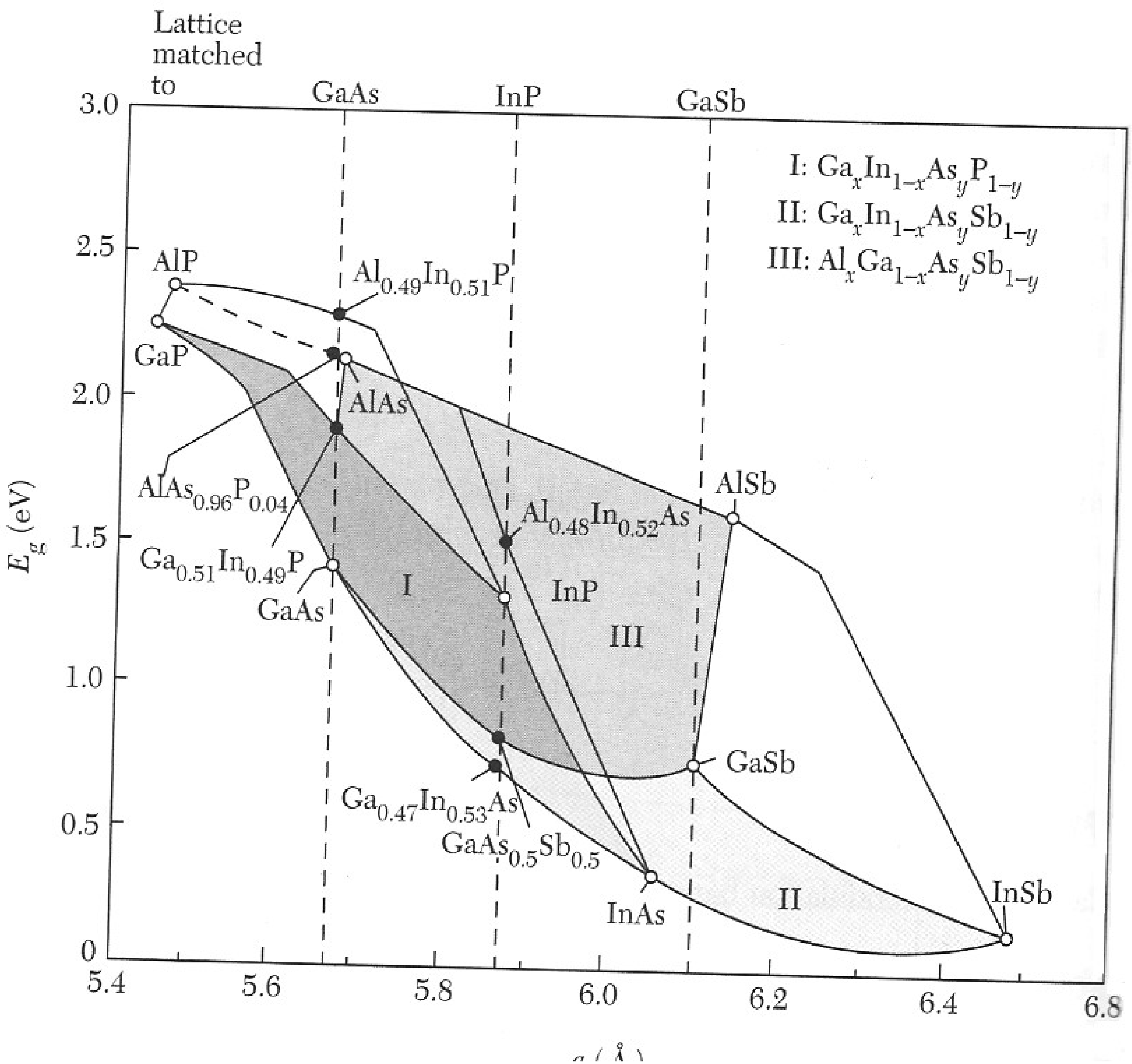
Light emitting diodes



absorption
reflection
total internal reflection

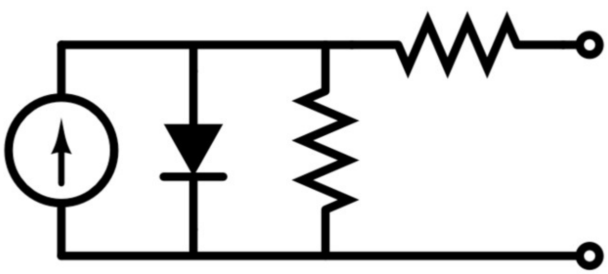


Electrons and holes are injected into the depletion region by forward biasing the junction. The electrons fall in the holes. For direct bandgap semiconductors, photons are emitted. For indirect bandgap semiconductors, phonons are emitted.

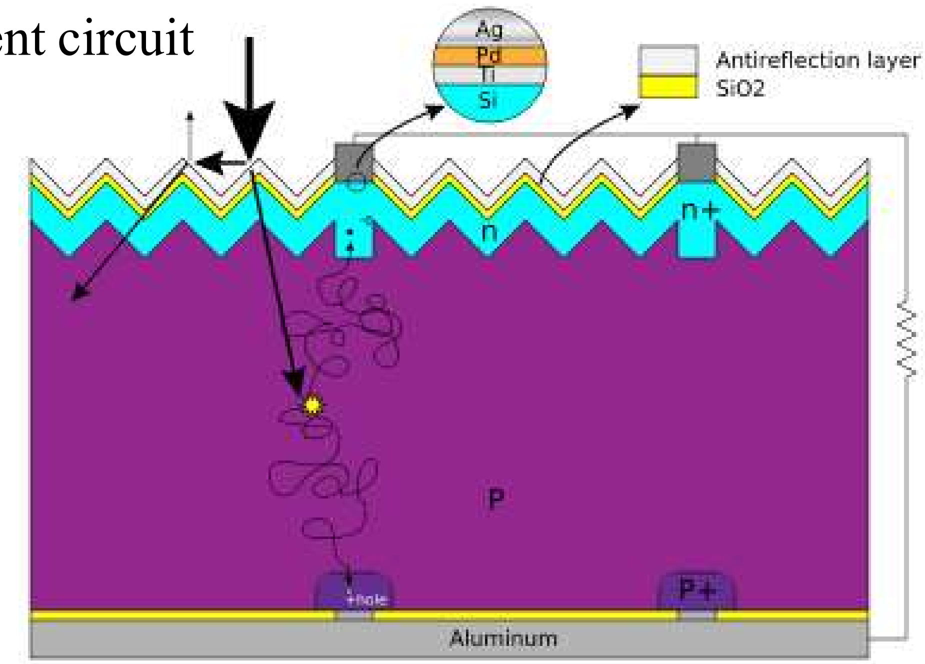


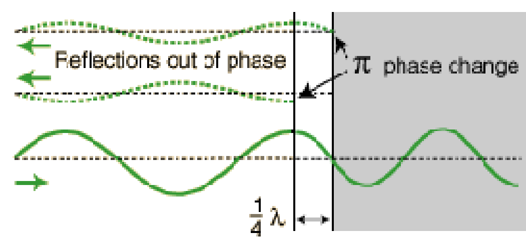
Lattice matched to
GaAs
InP
GaSb
3.0
2.5
2.0
1.5
1.0
0.5
0
E_g (eV)
I: $Ga_xIn_{1-x}As_yP_{1-y}$
II: $Ga_xIn_{1-x}As_ySb_{1-y}$
III: $Al_xGa_{1-x}As_ySb_{1-y}$
AlP
GaP
$Al_{0.49}In_{0.51}P$
AlAs
$AlAs_{0.96}P_{0.04}$
$Ga_{0.51}In_{0.49}P$
GaAs
I
$Al_{0.48}In_{0.52}As$
InP
III
AlSb
GaSb
$Ga_{0.47}In_{0.53}As$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

Solar cell

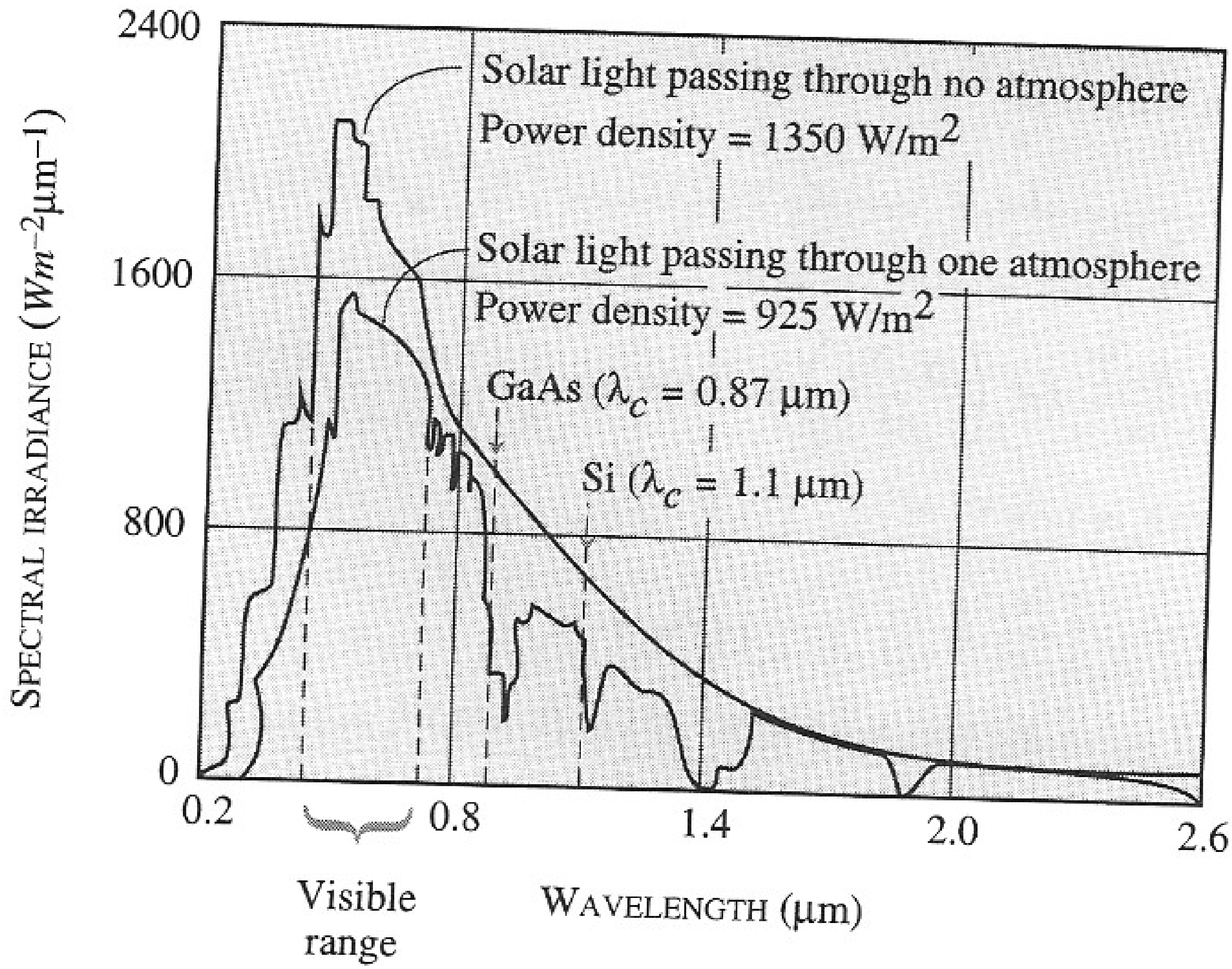


Equivalent circuit

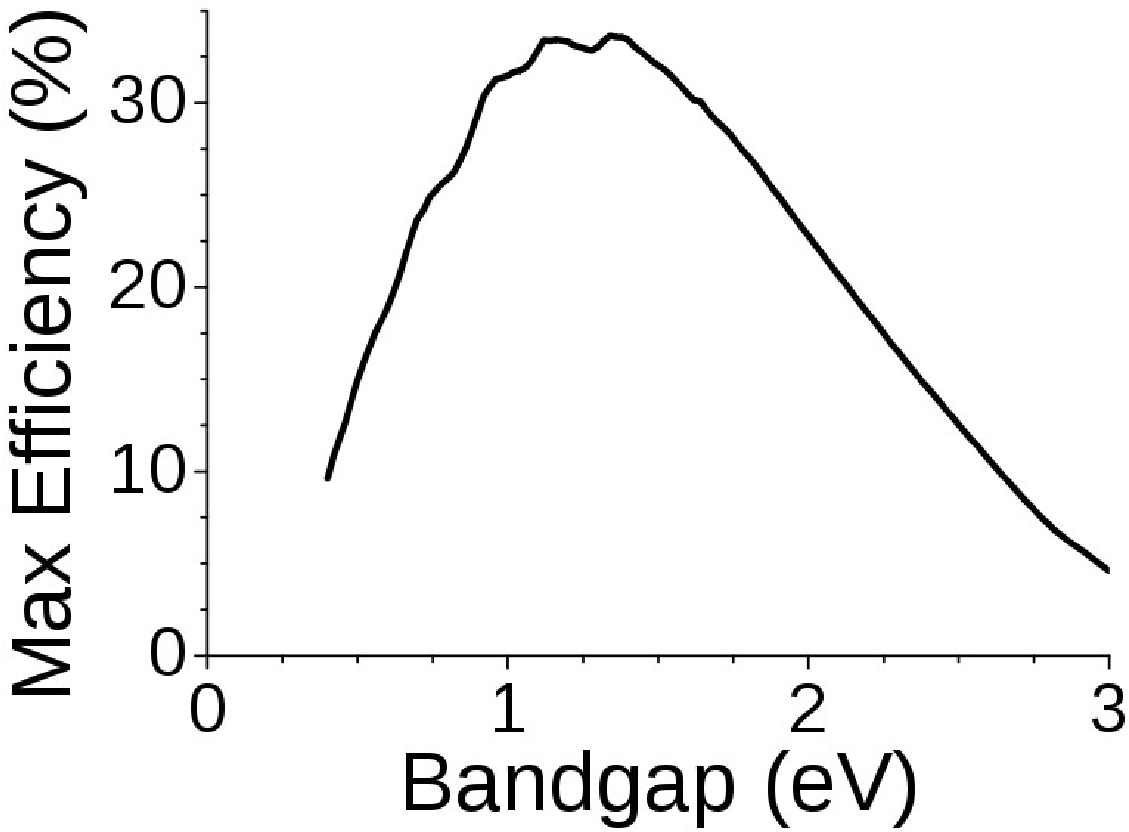




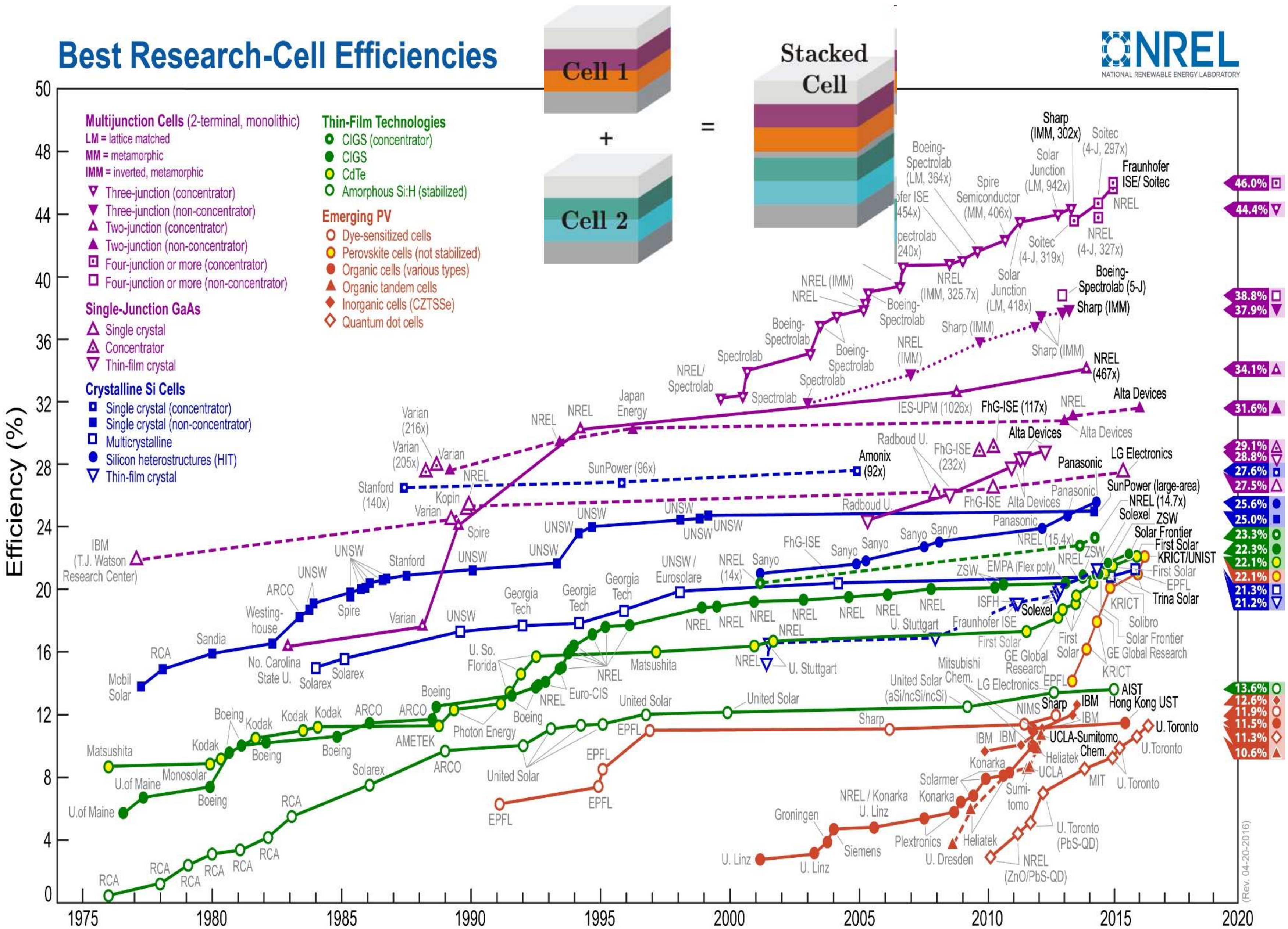
Solar spectrum



Shockley–Queisser limit



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



Biofuel efficiency ~ 1%

Grid parity will be reached in the next 10 years

http://www.nrel.gov/ncpv/images/efficiency_chart.jpg