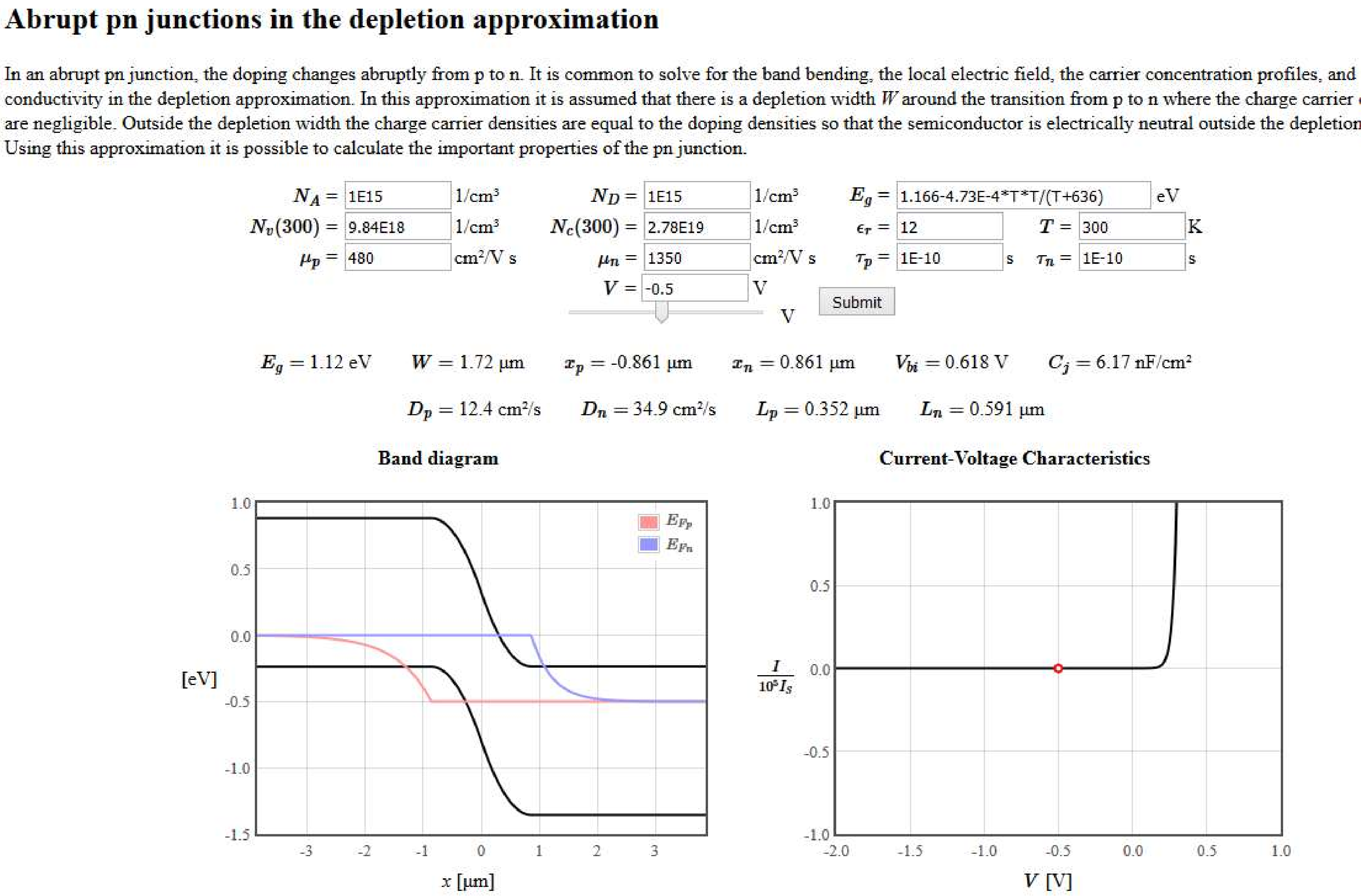


Abrupt pn junctions in the depletion approximation

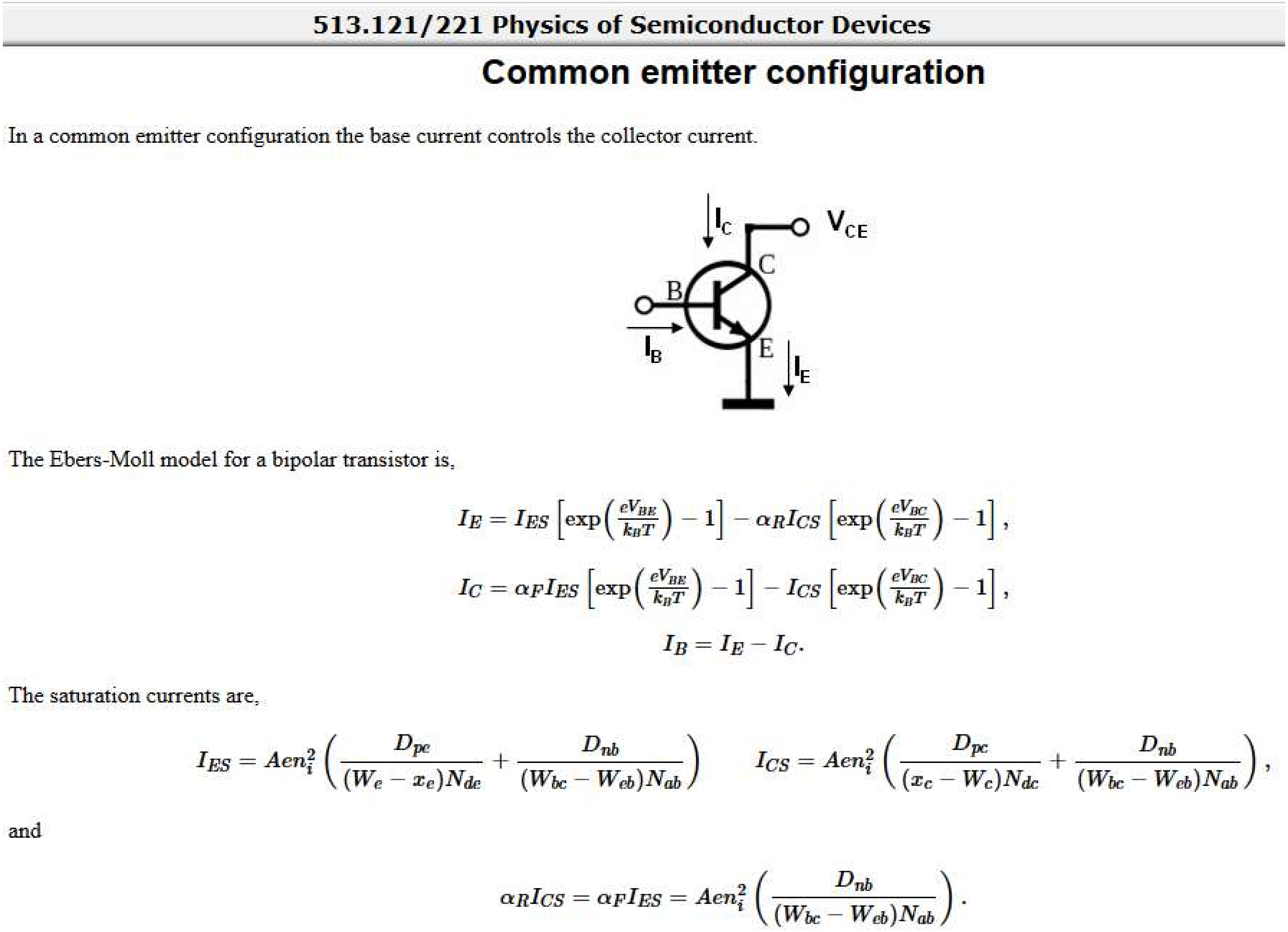
In an abrupt pn junction, the doping changes abruptly from p to n. It is common to solve for the band bending, the local electric field, the carrier concentration profiles, and conductivity in the depletion approximation. In this approximation it is assumed that there is a depletion width W around the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

$N_A =$ 1E15 1/cm³
$N_v(300) =$ 9.84E18 1/cm³
$\mu_p =$ 480 cm²/V s
$N_D =$ 1E15 1/cm³
$N_c(300) =$ 2.78E19 1/cm³
$\mu_n =$ 1350 cm²/V s
$E_g =$ 1.166-4.73E-4*T*T/(T+636) eV
$\epsilon_r =$ 12
$T =$ 300 K
$\tau_p =$ 1E-10 s
$\tau_n =$ 1E-10 s
$V =$ -0.5 V

$E_g = 1.12$ eV $W = 1.72$ µm $x_p = -0.861$ µm $x_n = 0.861$ µm $V_{bi} = 0.618$ V $C_j = 6.17$ nF/cm²

$D_p = 12.4$ cm²/s $D_n = 34.9$ cm²/s $L_p = 0.352$ µm $L_n = 0.591$ µm

http://lampx.tugraz.at/~hadley/psd/L6/abrupt.html



513.121/221 Physics of Semiconductor Devices

Common emitter configuration

In a common emitter configuration the base current controls the collector current.

The Ebers-Moll model for a bipolar transistor is,

$$I_E = I_{ES}\left[\exp\left(\frac{eV_{BE}}{k_BT}\right)-1\right] - \alpha_R I_{CS}\left[\exp\left(\frac{eV_{BC}}{k_BT}\right)-1\right],$$

$$I_C = \alpha_F I_{ES}\left[\exp\left(\frac{eV_{BE}}{k_BT}\right)-1\right] - I_{CS}\left[\exp\left(\frac{eV_{BC}}{k_BT}\right)-1\right],$$

$$I_B = I_E - I_C.$$

The saturation currents are,

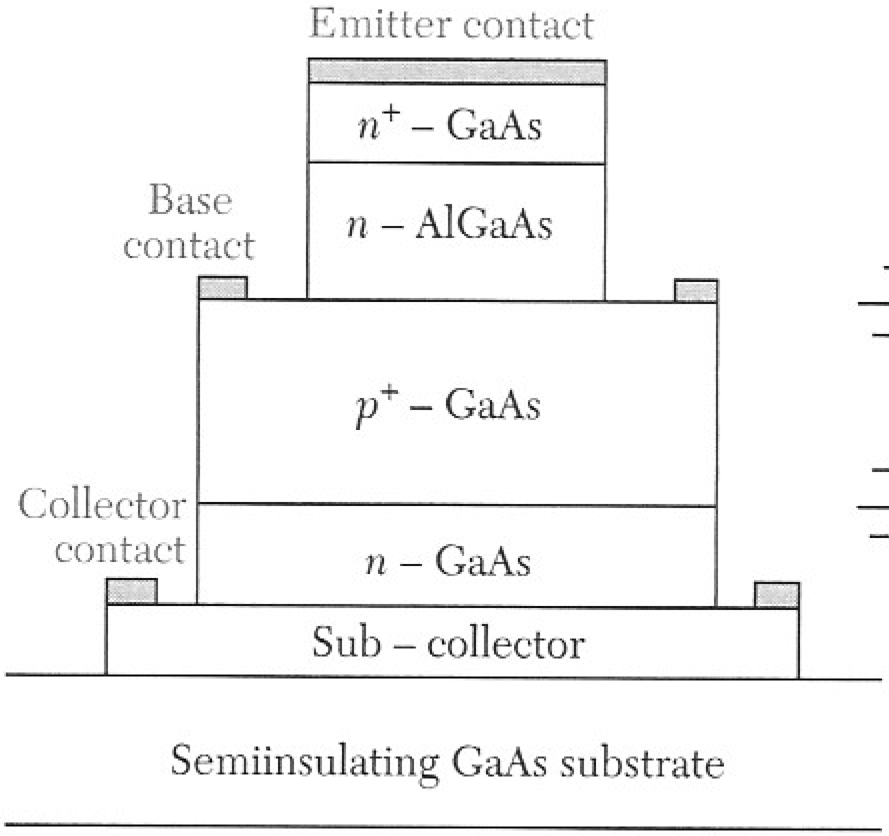
$$I_{ES} = Aen_i^2\left(\frac{D_{pe}}{(W_e - x_e)N_{de}} + \frac{D_{nb}}{(W_{bc} - W_{eb})N_{ab}}\right) \qquad I_{CS} = Aen_i^2\left(\frac{D_{pc}}{(x_c - W_c)N_{dc}} + \frac{D_{nb}}{(W_{bc} - W_{eb})N_{ab}}\right),$$

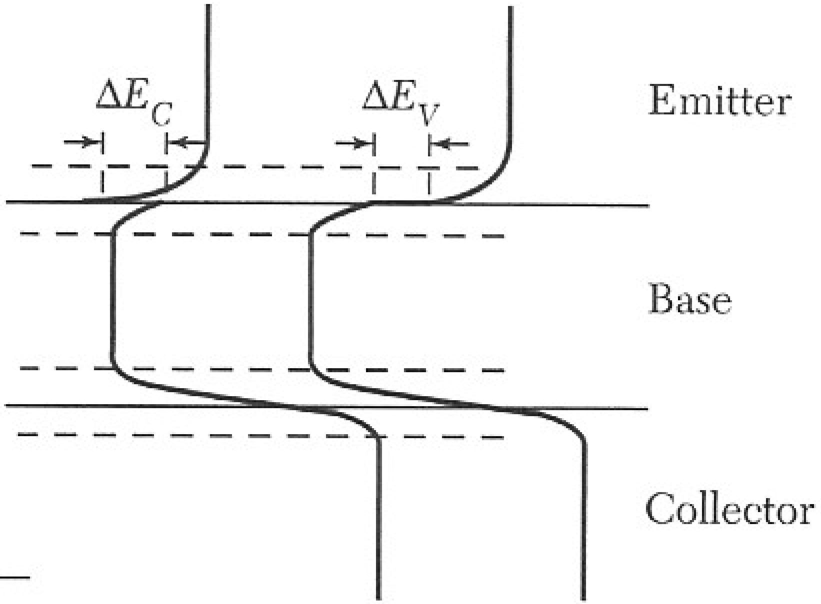
and

$$\alpha_R I_{CS} = \alpha_F I_{ES} = Aen_i^2\left(\frac{D_{nb}}{(W_{bc} - W_{eb})N_{ab}}\right).$$

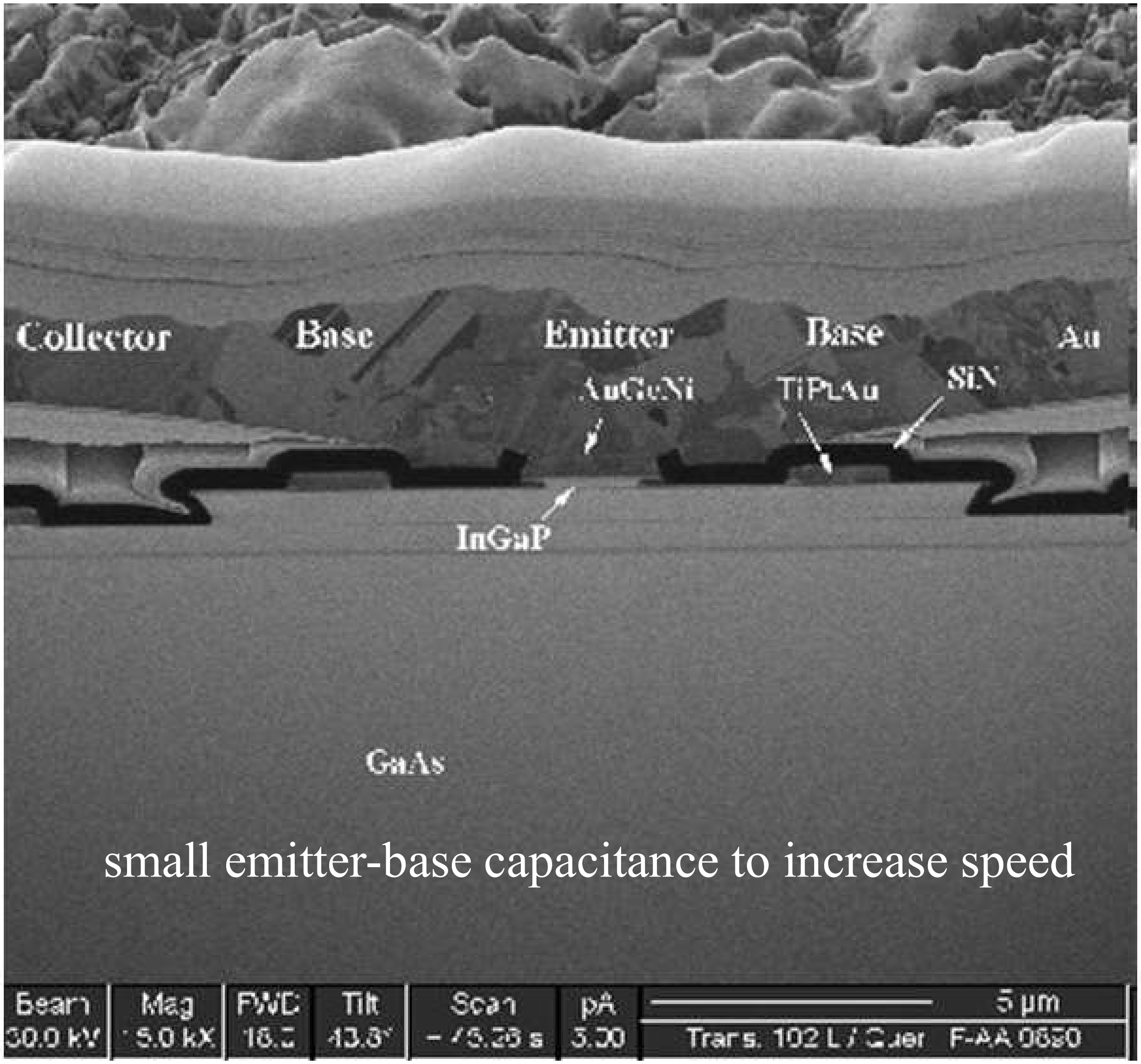
http://lampx.tugraz.at/~hadley/psd/L13/commonemitter.php

Heterojunction bipolar transistors





Heterojunction bipolar transistor



small emitter-base capacitance to increase speed

HBT current gain

$$I_C = \beta I_B$$

$$\beta = \frac{\alpha}{1-\alpha} \approx \frac{n_{B0}}{p_{E0}} \qquad \text{(npn)}$$

Higher doping in the emitter makes the minority carrier concentration lower in the emitter.

$$n_{B0} = \frac{n_i^2}{N_A} = \frac{N_C N_V \exp(-E_{gB}/k_B T)}{N_A}$$

$$p_{E0} = \frac{n_i^2}{N_D} = \frac{N'_C N'_V \exp(-E_{gE}/k_B T)}{N_D}$$

If the emitter and the base have different band gaps

$$\beta = \frac{N_E}{N_B}\frac{N_c N_v}{N'_c N'_v}\exp\left(\frac{\Delta E_g}{k_B T}\right) \;\square\; 100000$$

HBT current gain

A HBT has an emitter bandgap of 1.62 and a base bandgap of 1.42.
A BJT has an emitter bandgap of 1.42 and a base bandgap of 1.42.
Both have an emitter doping of 10^{18} cm^{-3} and a base doping of 10^{15}cm^{-3}.
How much larger is the gain in the HBT?

$$\frac{\beta(\mathrm{HBT})}{\beta(\mathrm{BJT})} = \exp\left(\frac{\Delta E_g}{k_B T}\right) = \exp\left(\frac{1.62 - 1.42}{0.0259}\right) = 2257$$

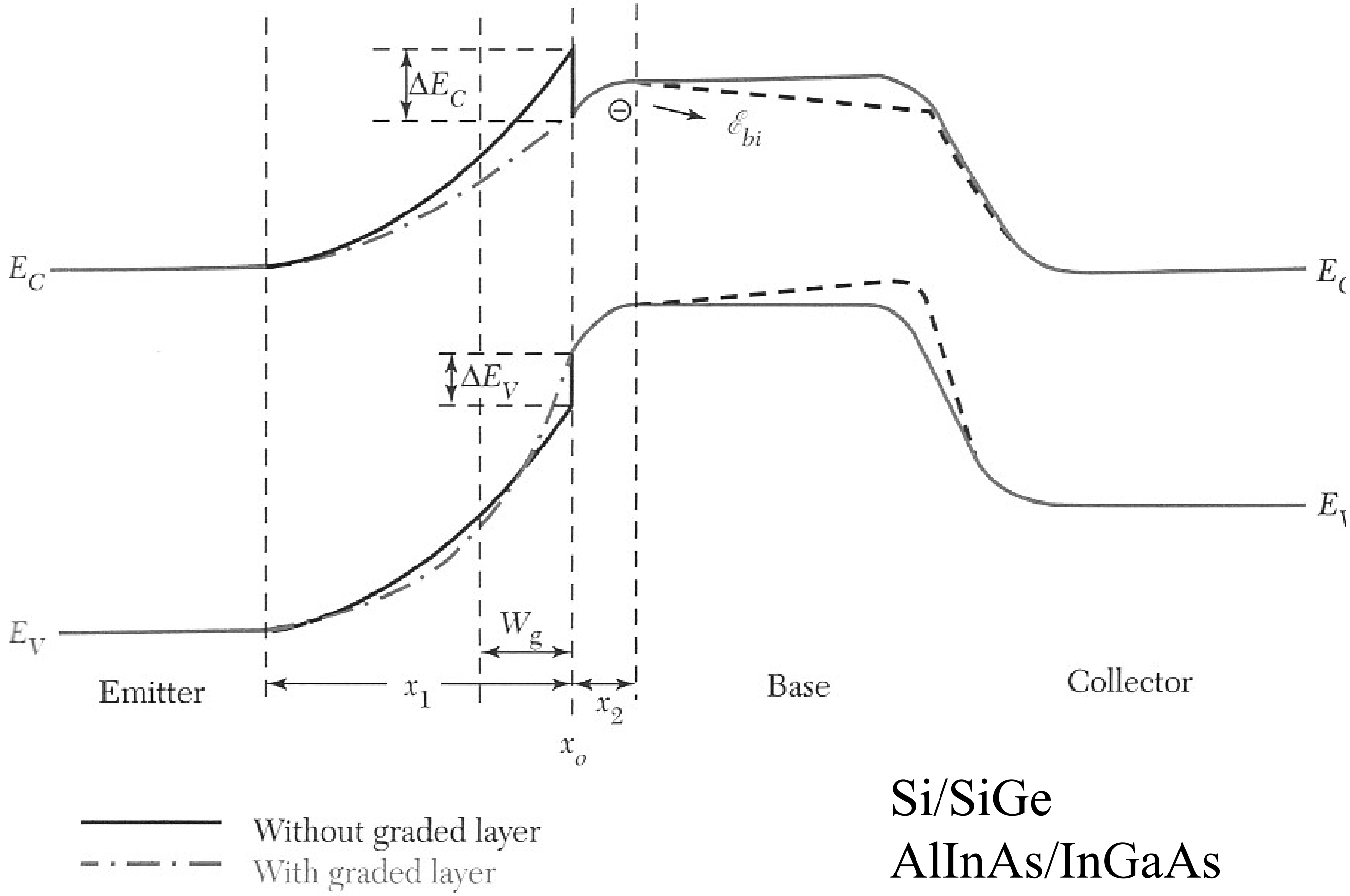
HBT

Trade off gain for higher speed

Higher base doping
- lower base resistance
- reduced Early effect
- less trouble with punch through
- base can be made thinner -> faster transistors

Because of higher base doping, a higher collector doping is possible without punch through
- lower collector resistance

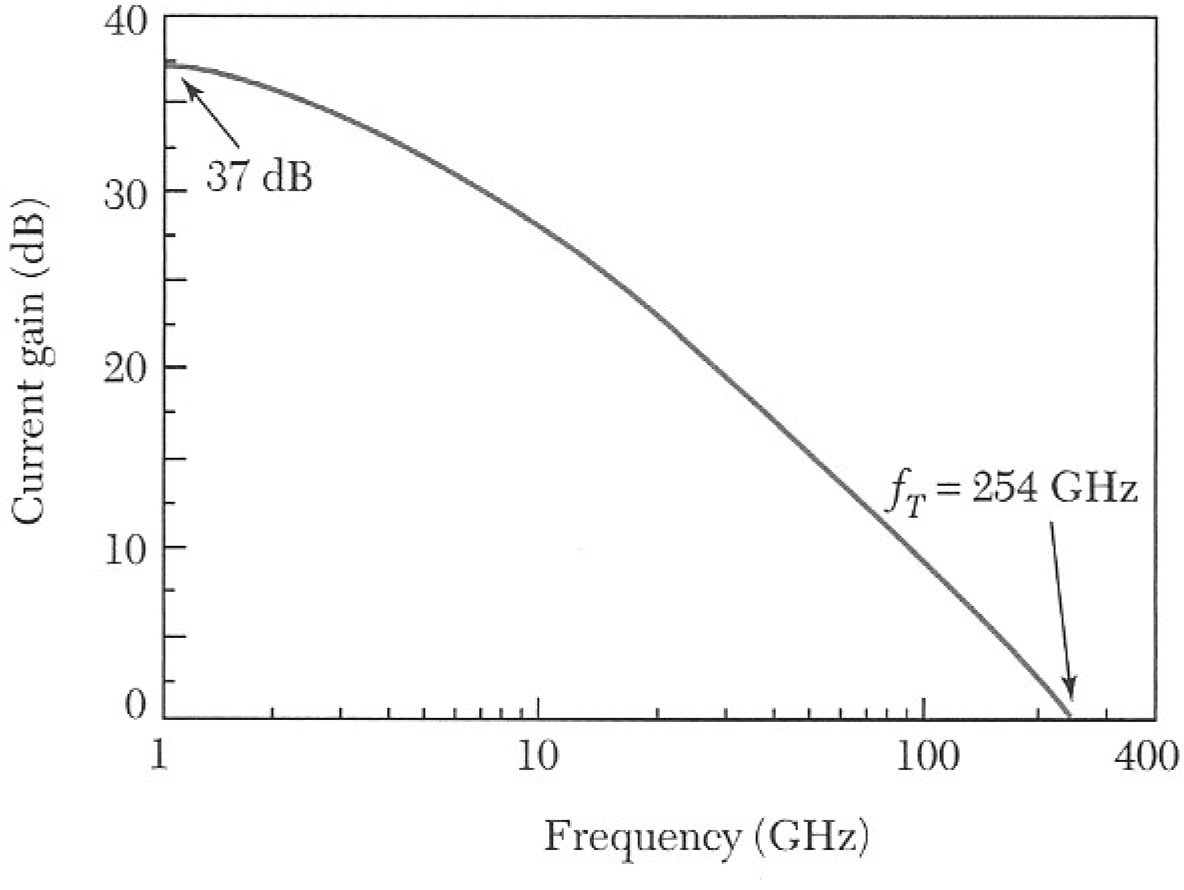
HBT current gain



Si/SiGe
AlInAs/InGaAs

band discontinuity reduces emitter efficiency
Graded layer emitter and base improve performance

Heterojunction bipolar transistors



Fastest InP/InGaAs HBT's have an f_T of 710 GHz.

Higher doping in the base allows for a thinner base without punch through and lower base resistance and thus higher frequency operation

Microwave engineering

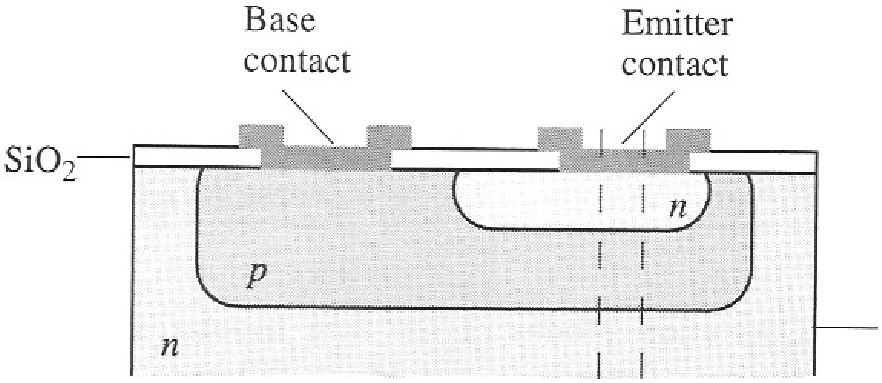
Electronics: $L << \lambda$ $f <\sim 10$ GHz

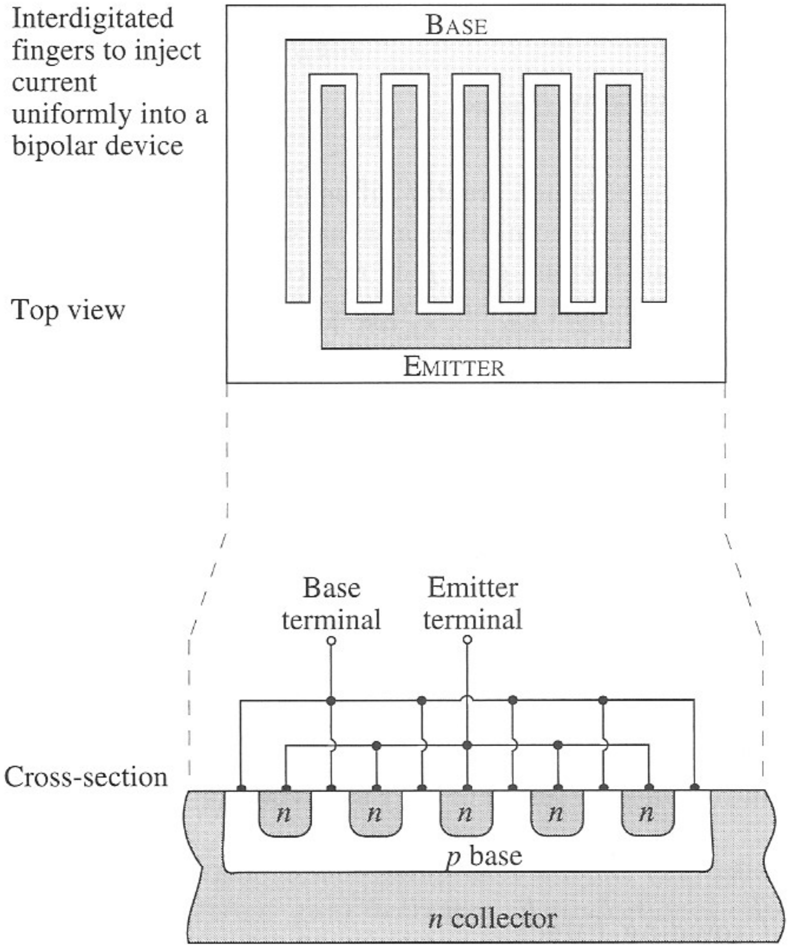
Microwave: $\lambda < L$ 10 GHz $< f <$ 1 THz

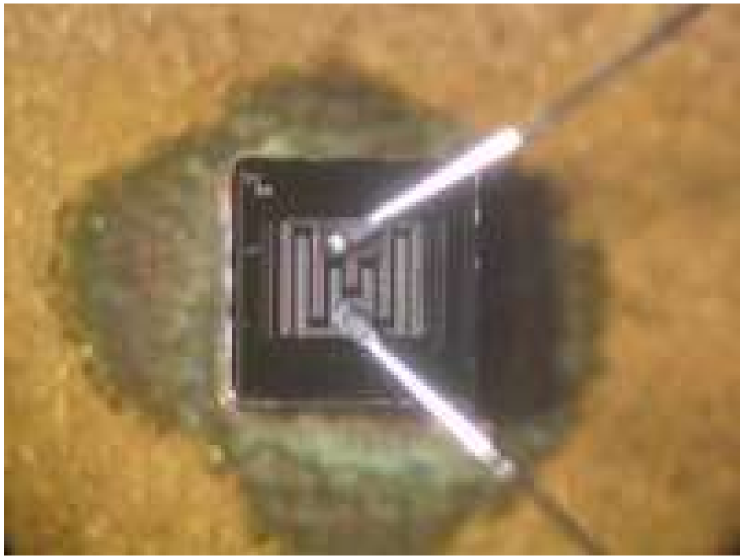
TeraHertz: $\lambda << L$ 1 THz $< f <$ 100 THz

Optics: $\lambda << L$ 100 THz $< f$

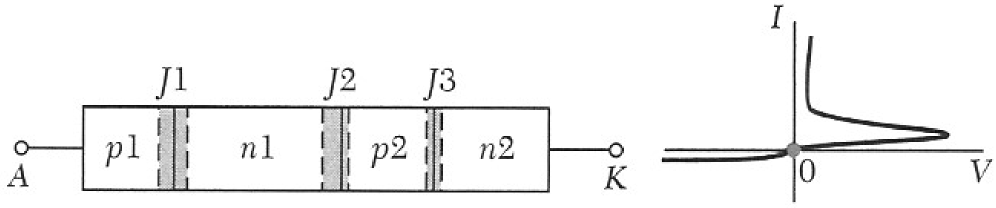
Interdigitated contacts in power transistors



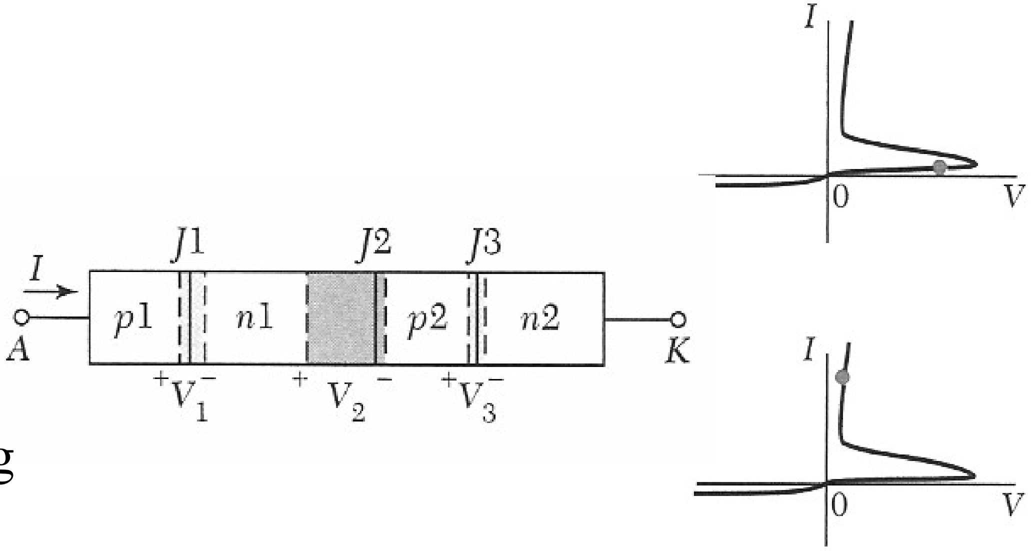




Thyristors

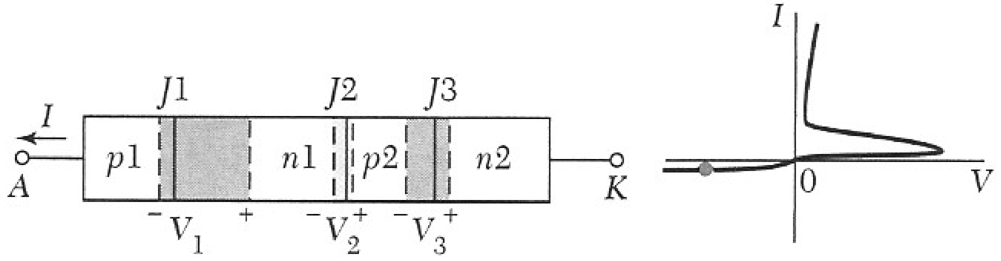


Forward blocking

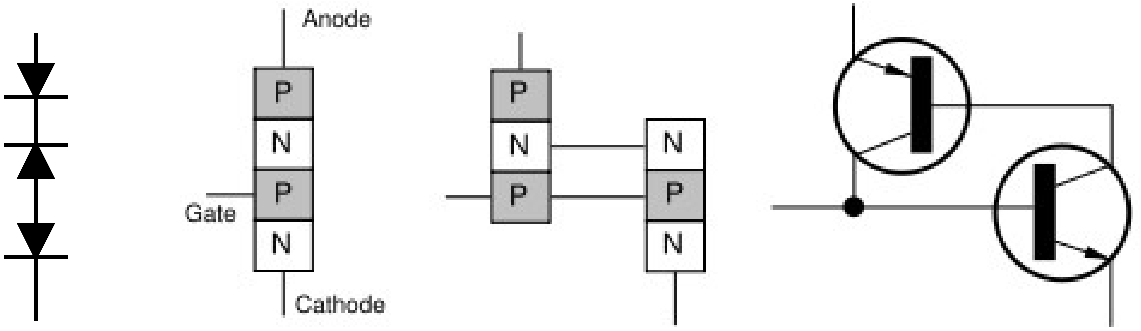


Forward conducting

Reverse blocking

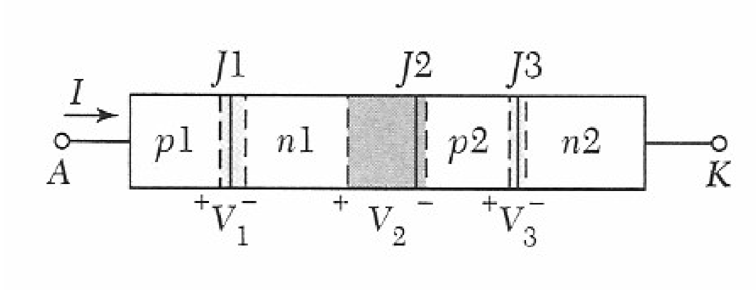


Thyristors

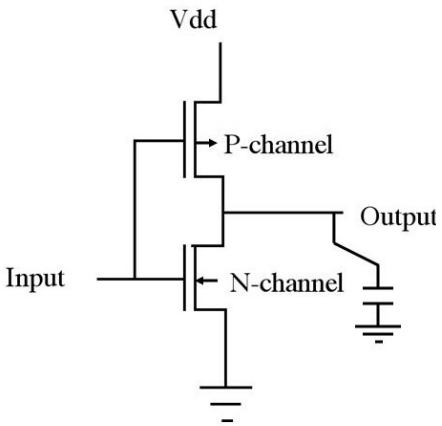


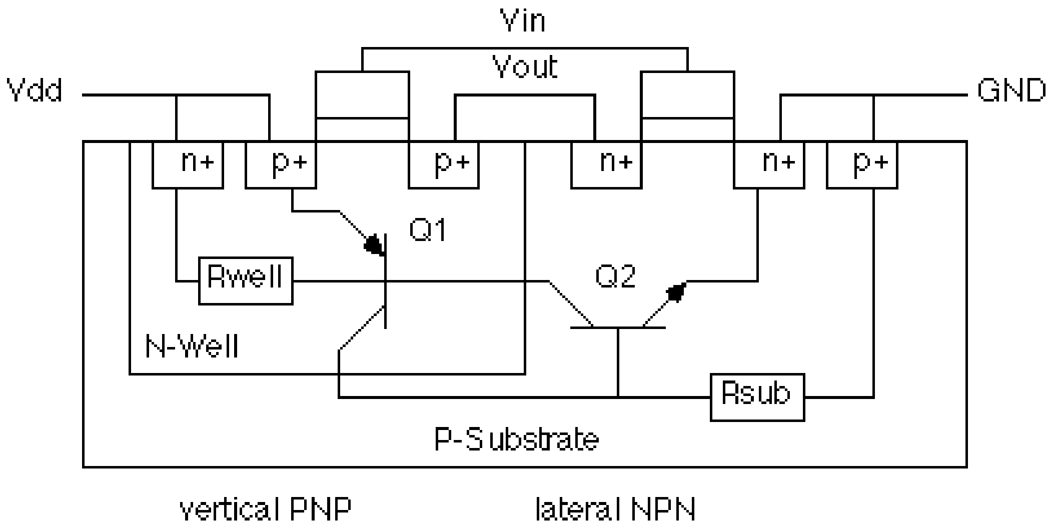
$\beta_1 * \beta_2 > 1$

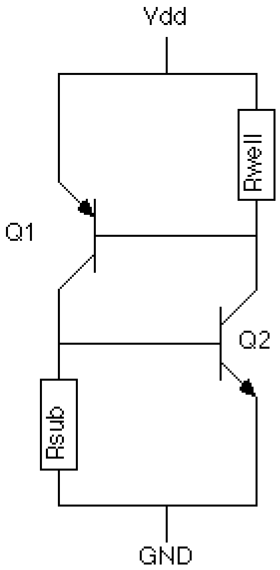
Used for switching high currents or voltages



Latch-up



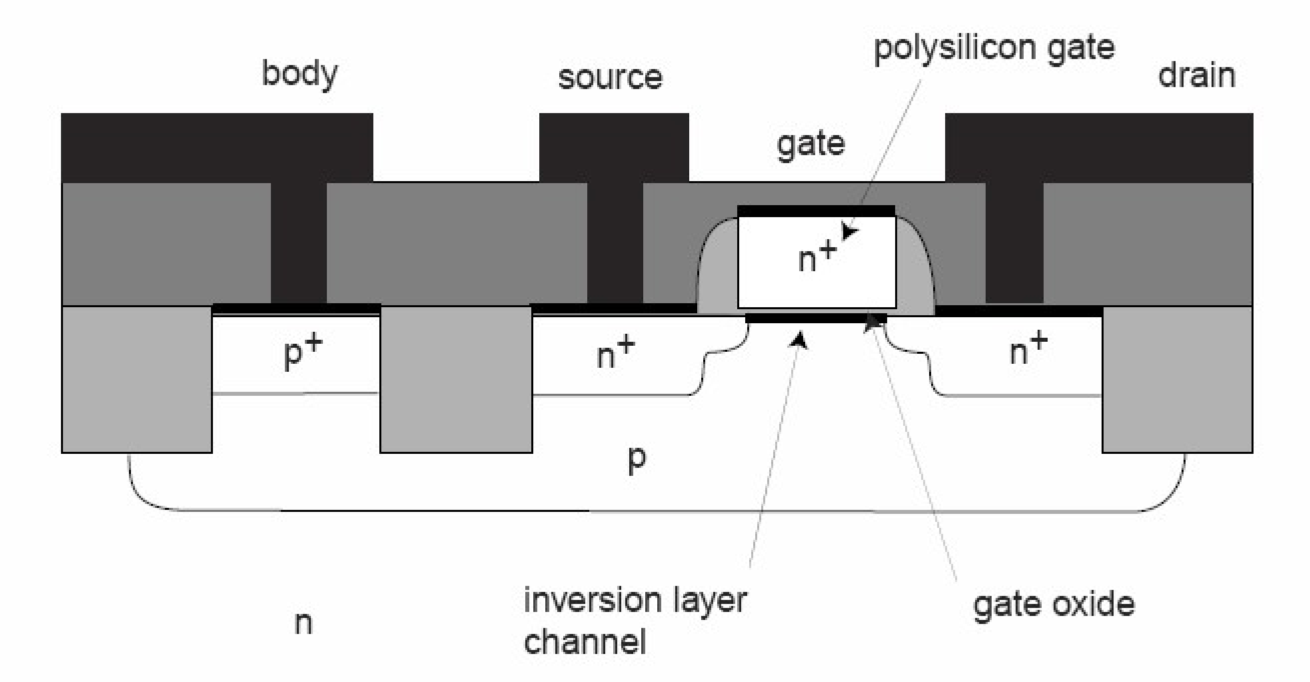




Both BJT's conduct, creating a low resistance path between V_{dd} and GND. The product of the gains of the two transistors in the feedback loop, is greater than one. The result of latchup is at the minimum a circuit malfunction, and in the worst case, the destruction of the device.

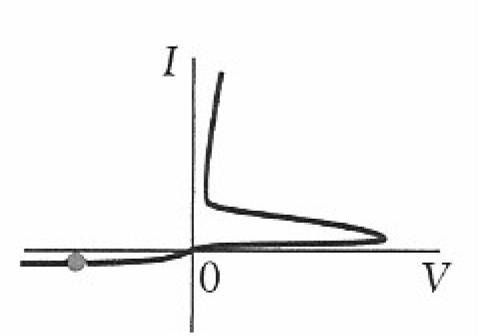
http://www.ece.drexel.edu/courses/ECE-E431/latch-up/latch-up.html

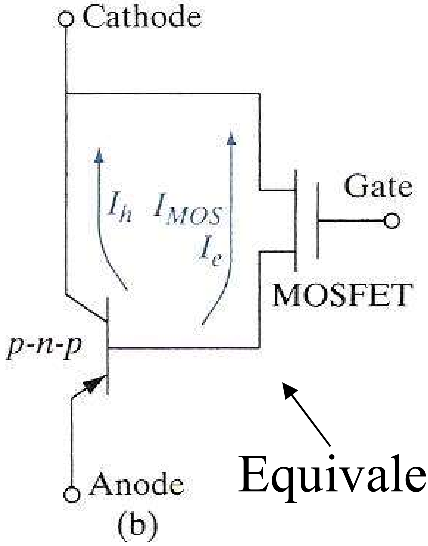
Subthreshold current



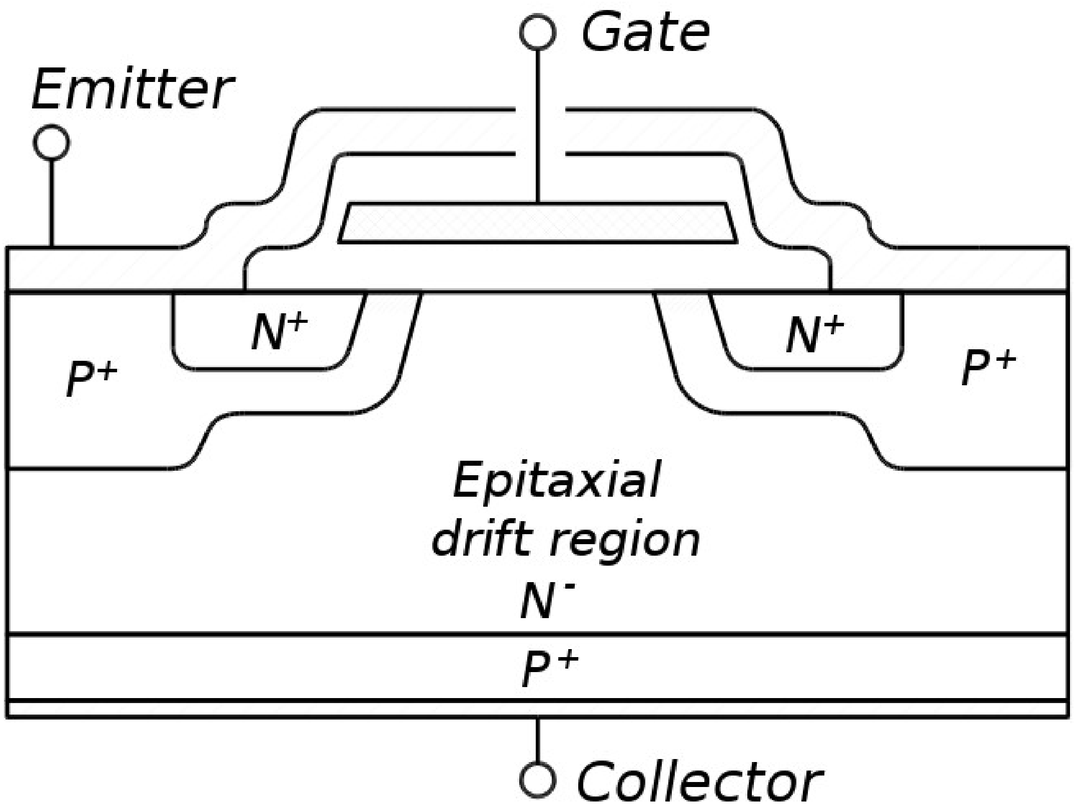
If the p-concentration in the channel is low, electrons emitted into the channel by the forward biased junction diffuse across the channel without recombining.

Insulated gate bipolar transistor (IGBT)





Equivalent circuit in the on-state. From Streetman.



Used to switch large currents (in electric cars or trains).

Optoelectronics

light emitting diode
laser diode
solar cell
waveguide
photo detectors

communications, memory (DVD), displays, printing, bar-code readers, solar energy, lighting, computing, 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

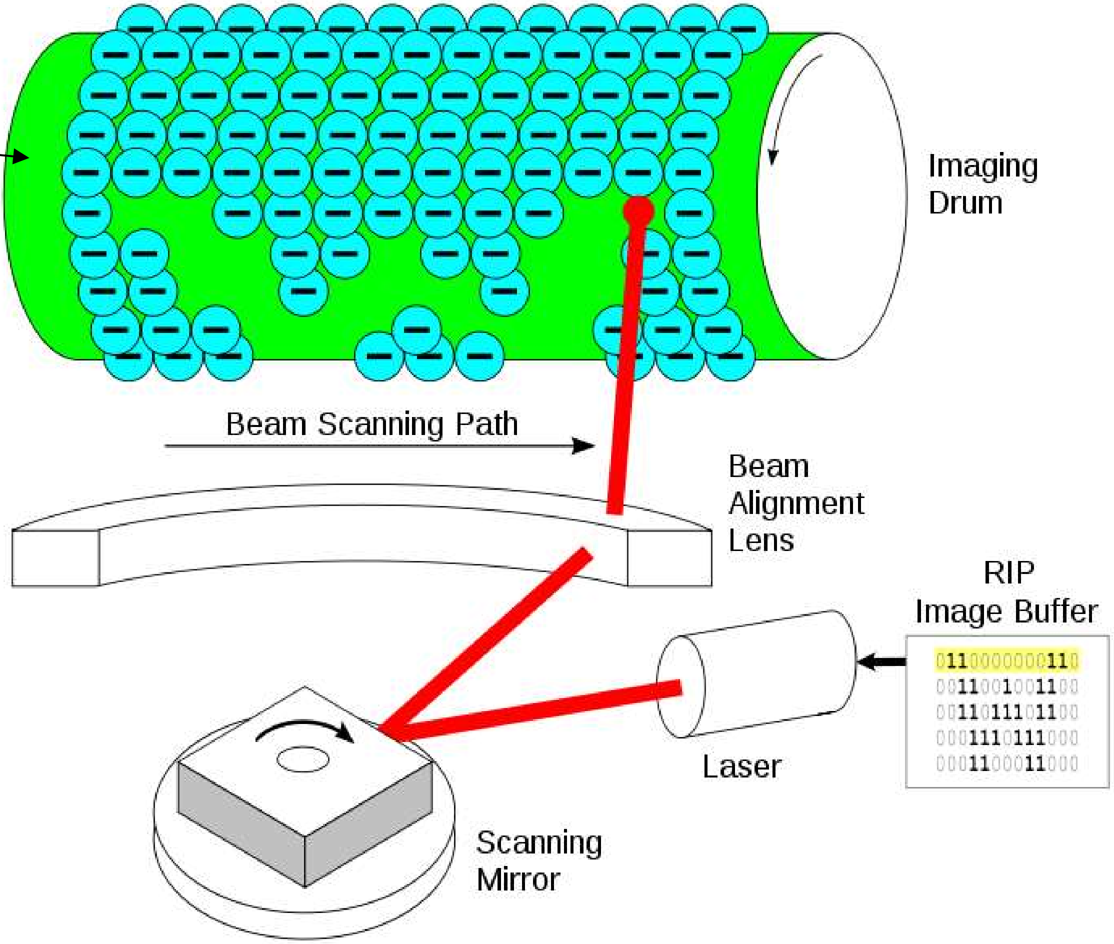
Reverse biased pn junction - smaller capacitance, higher speed, less noise

Phototransistor - light injects carriers into the base. This current is amplified. 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

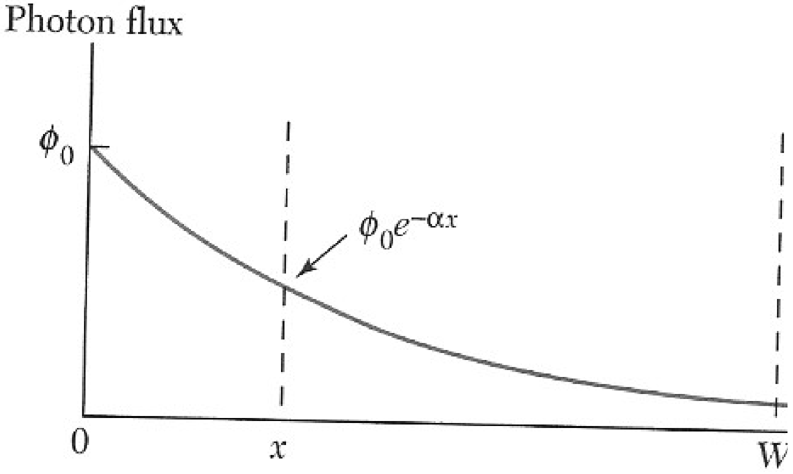


semiconducting
photoconductor

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

Absorption

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

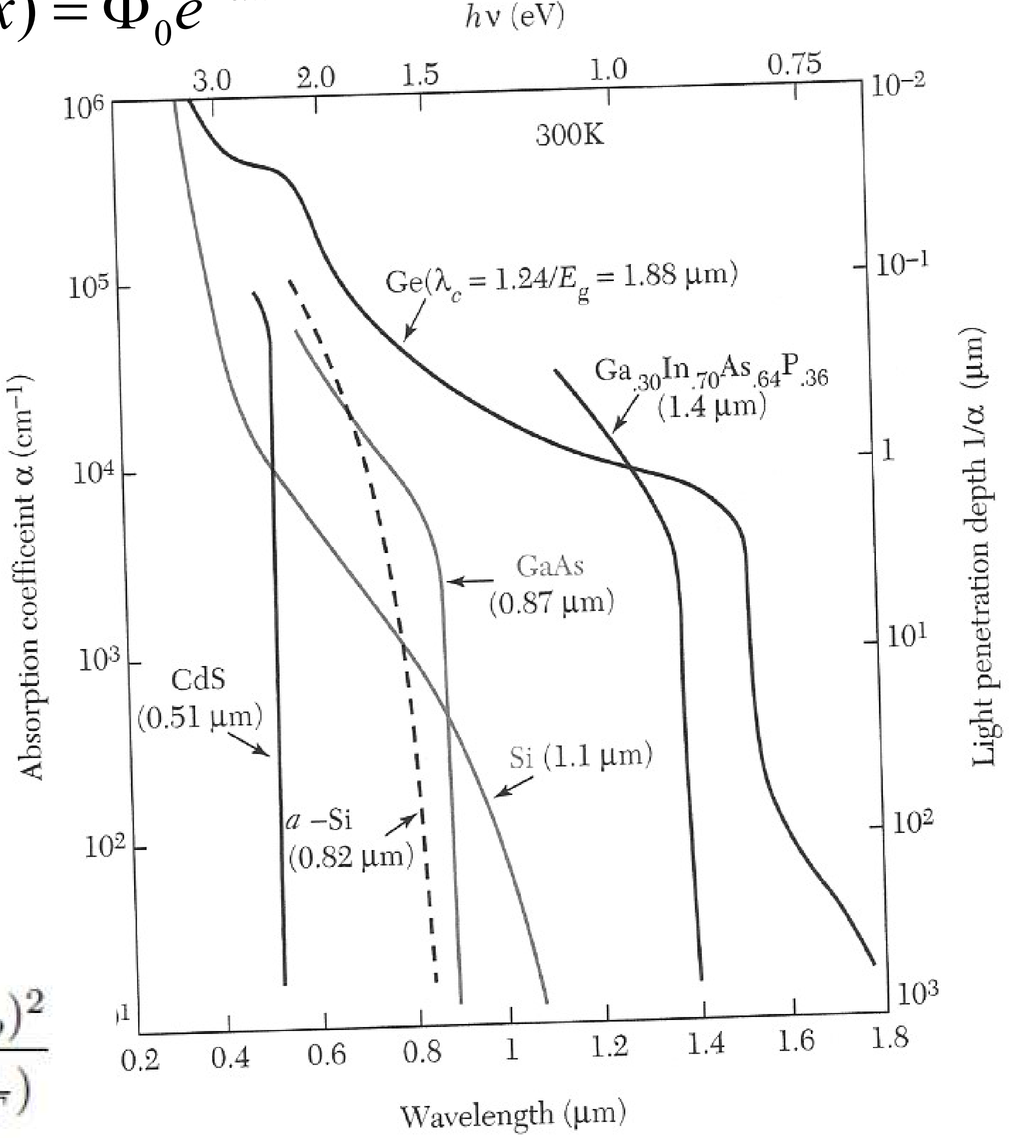


Sharp absorption edge for direct bandgap materials

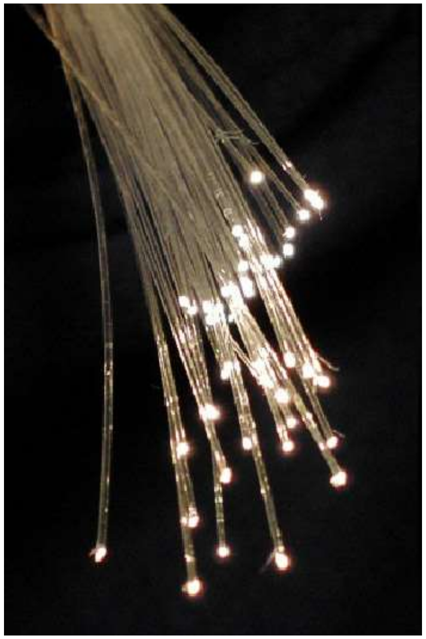
$$\alpha \approx 3.5\times10^{6}\left(\frac{m_r^*}{m_0}\right)^{3/2}\frac{\sqrt{\hbar\omega - E_g}}{\hbar\omega} \quad \text{cm}^{-1}$$

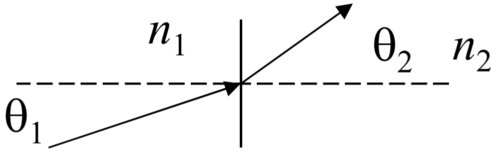
direct bandgap   indirect bandgap

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

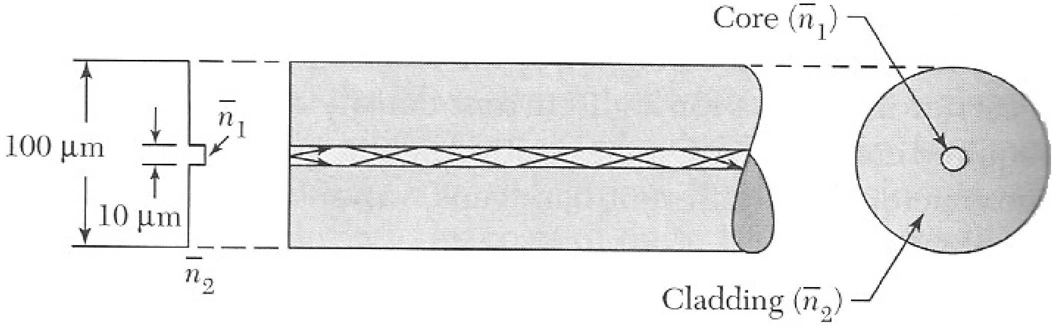


Confinement of light by total internal reflection

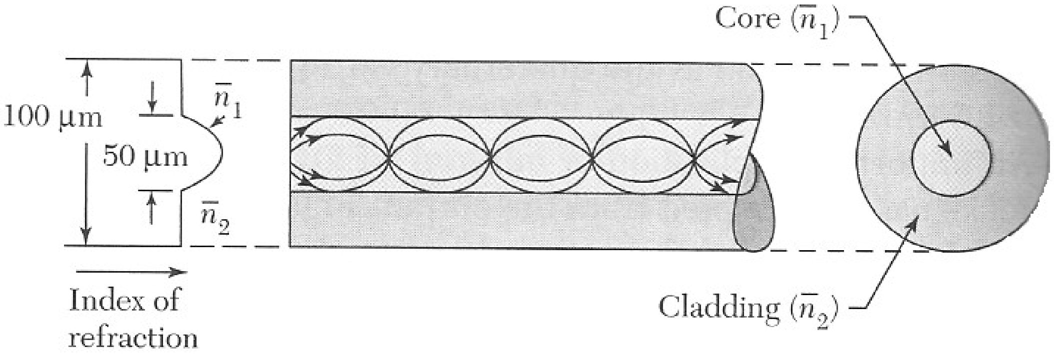


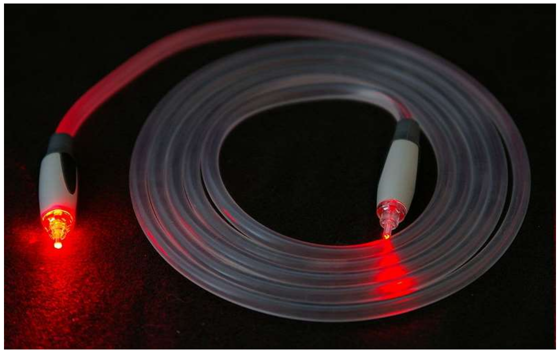


$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

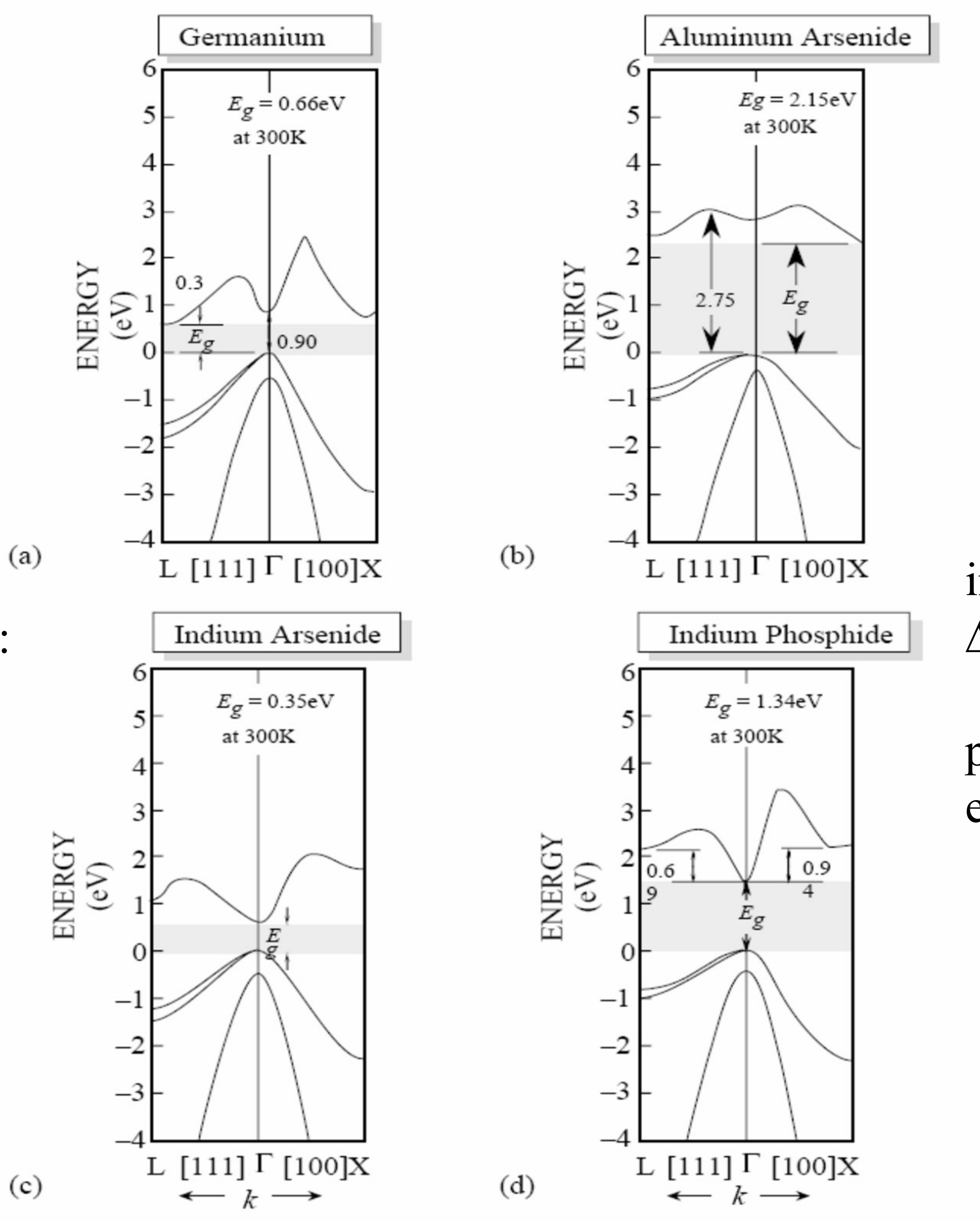


less pulse spreading for parabolically graded fiber





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



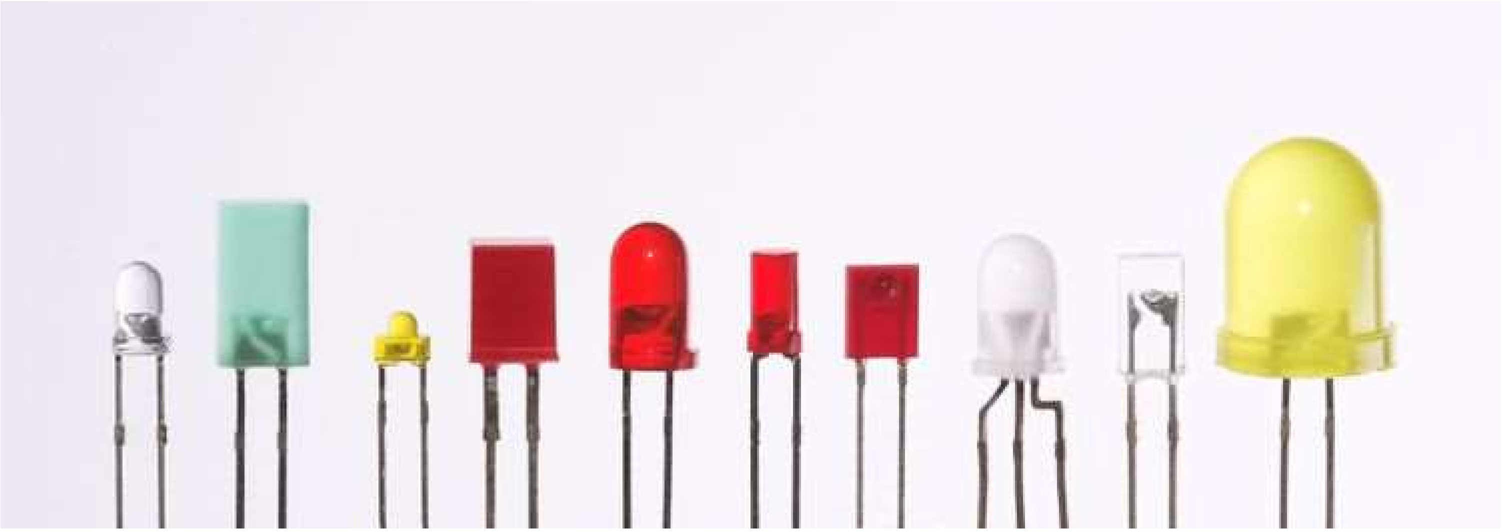
direct bandgap:
$\Delta k = 0$

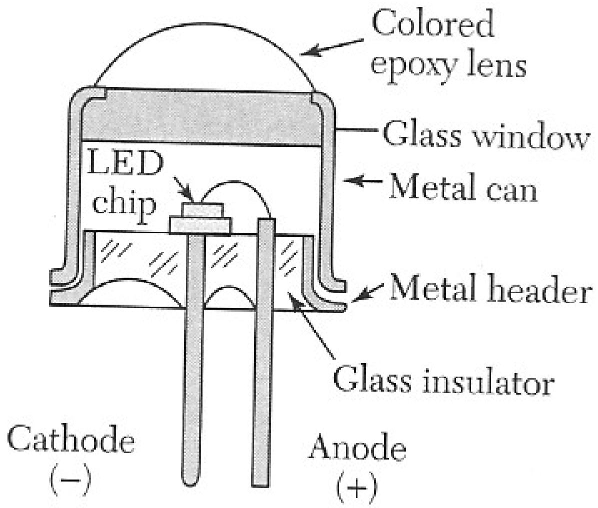
photons can be
emitted

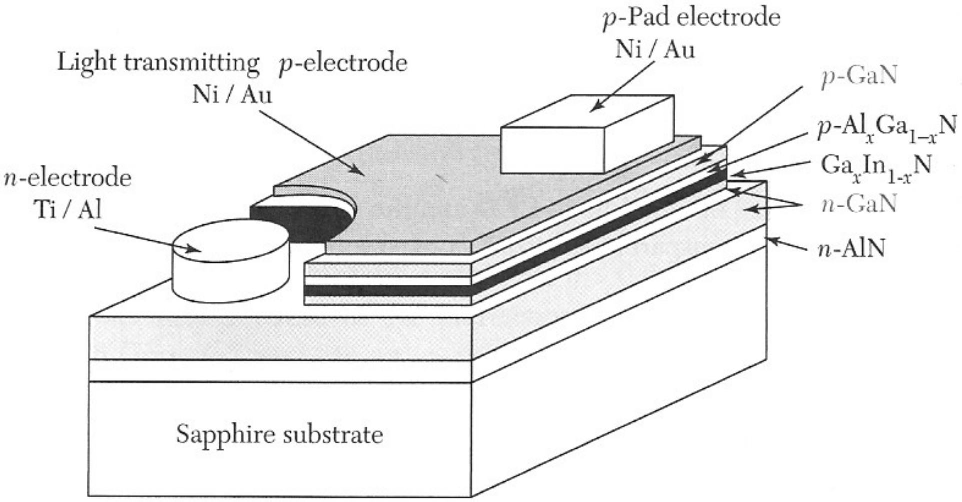
indirect bandgap:
$\Delta k \neq 0$

phonons are
emitted

Light emitting diodes







Solid state lighting is efficient.

Light emitting diodes

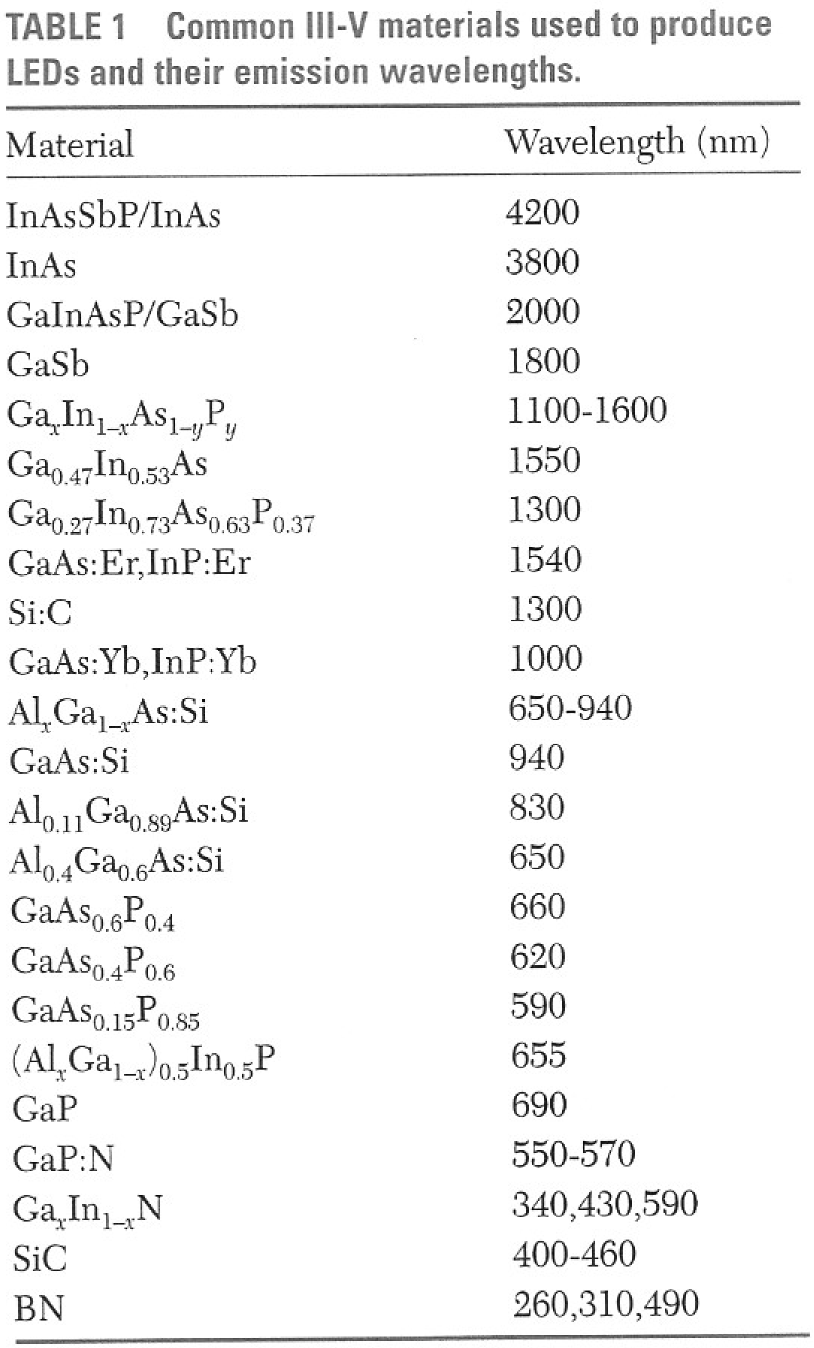
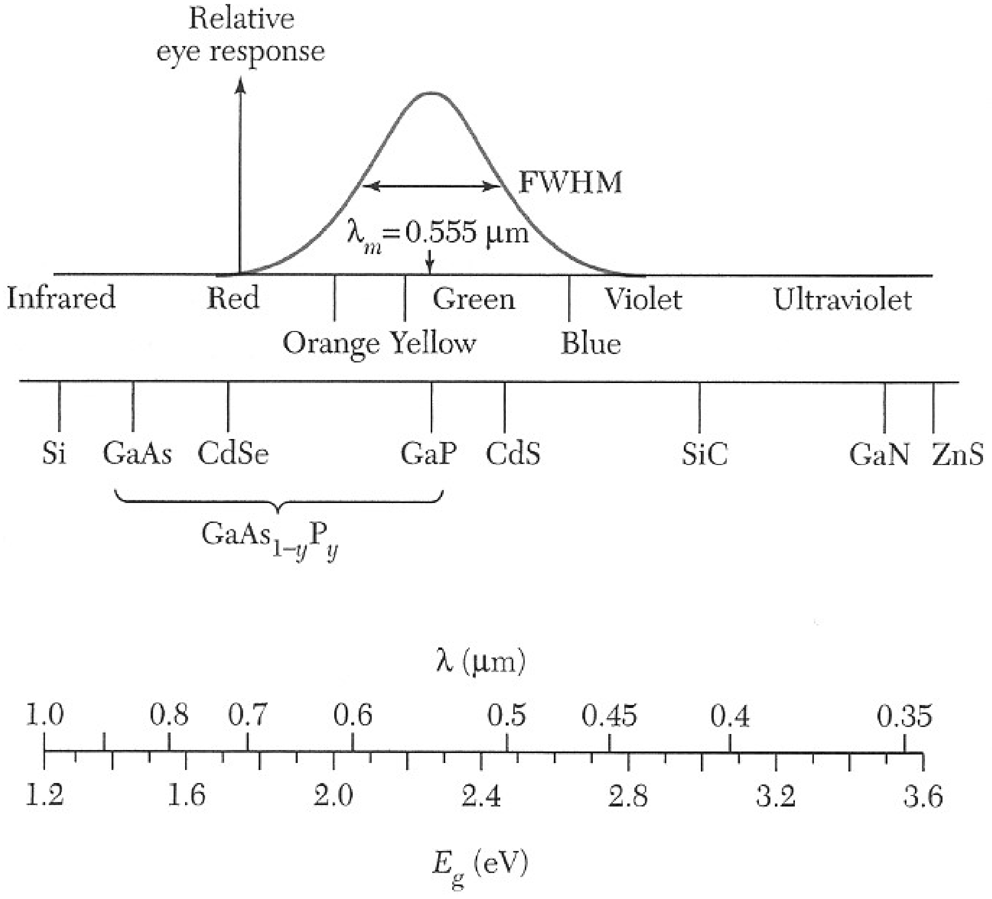
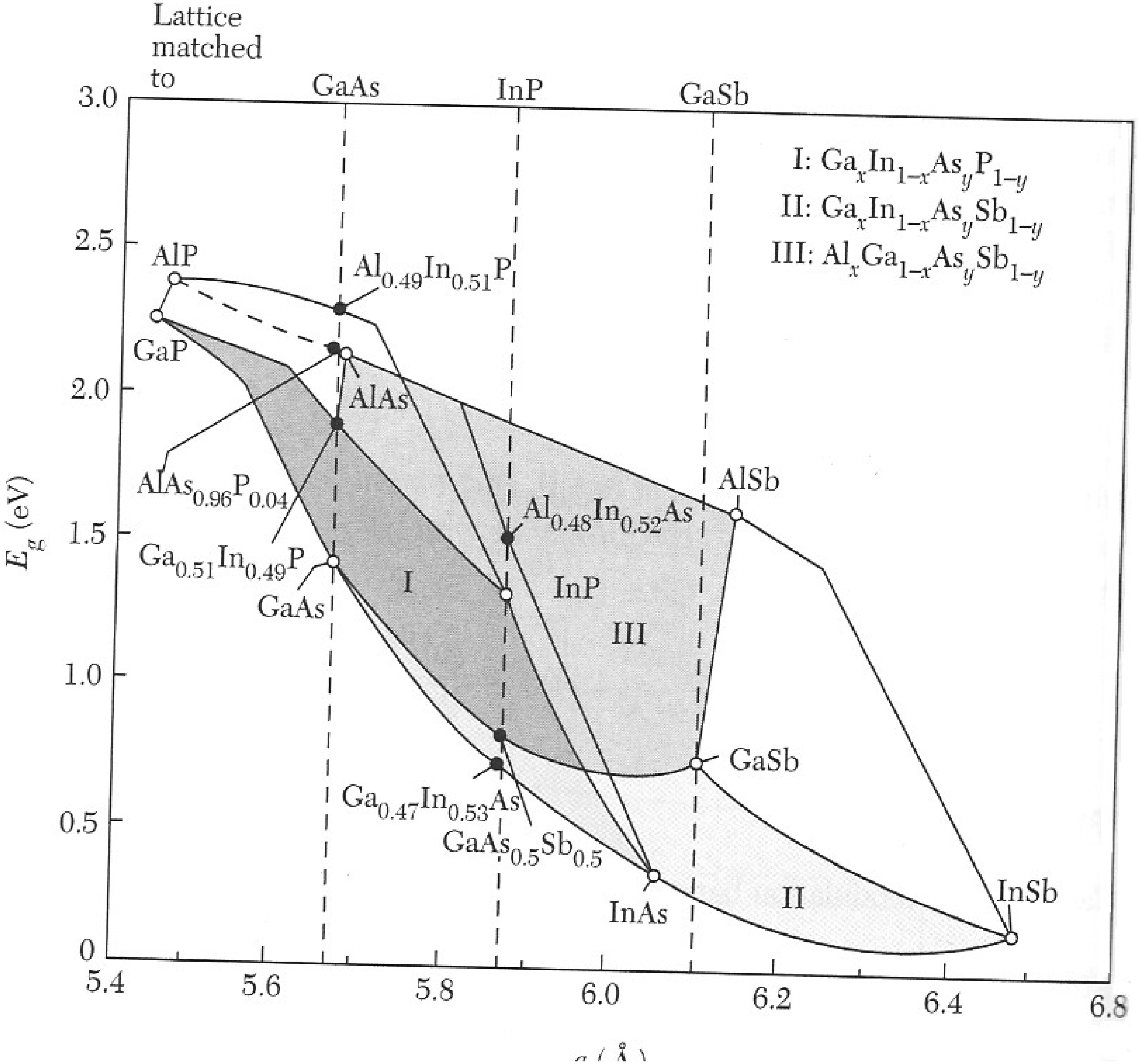


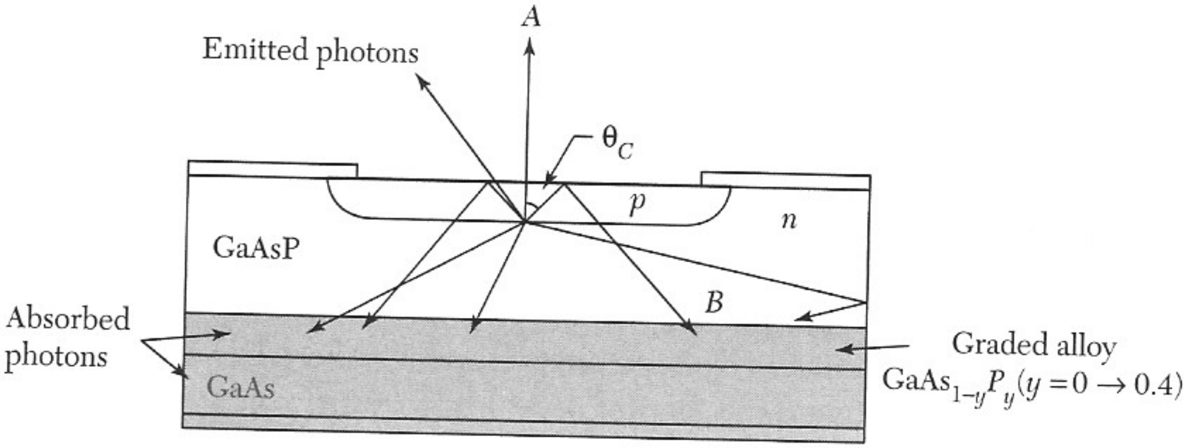
TABLE 1 **Common III-V materials used to produce LEDs and their emission wavelengths.**

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

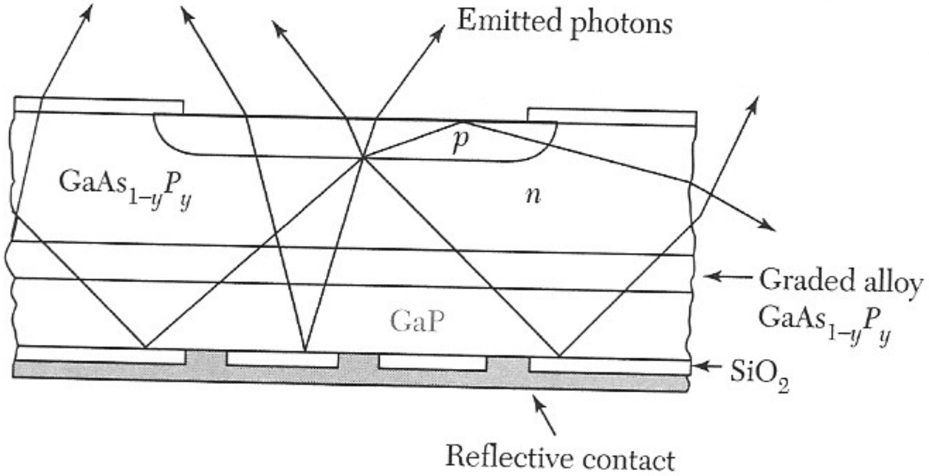



Lattice matched to
GaAs
InP
GaSb
I: $Ga_xIn_{1-x}As_yP_{1-y}$
II: $Ga_xIn_{1-x}As_ySb_{1-y}$
III: $Al_xGa_{1-x}As_ySb_{1-y}$
AlP
GaP
$Al_{0.49}In_{0.51}P$
AlAs
$AlAs_{0.96}P_{0.04}$
$Ga_{0.51}In_{0.49}P$
GaAs
I
InP
III
$Al_{0.48}In_{0.52}As$
AlSb
GaSb
$Ga_{0.47}In_{0.53}As$
$GaAs_{0.5}Sb_{0.5}$
InAs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

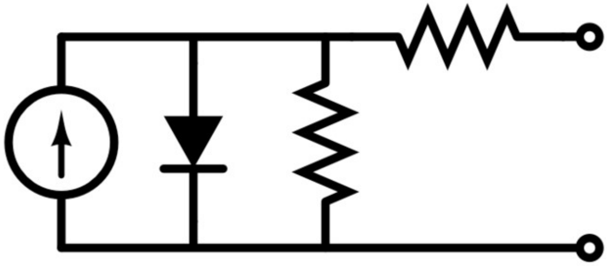
Light emitting diodes



absorption
reflection
total internal reflection



Solar cell



Equivalent circuit