Light-Emitting Diodes

Light Emission via Excitonic Transitions

a) GaP: Zn-O system (Red light)

b) GaP: N system (Green light)

In both of these systems the emission of light is much more intense than expected in a n-p junction GaP device having indirect band-to-band type transitions. The reason is the formation of excitons in the p-region where minority electrons are injected. The decay of excitons, yielding photons, is more probable than photon emission involving indirect transition (band-to-band).

GaP - Zn-O system

Figure 1 shows the n-p GaP diode under forward-biased condition. (n-type dopants in GaP are Se and Te. p-type dopants in GaP are Zn and Cd.)

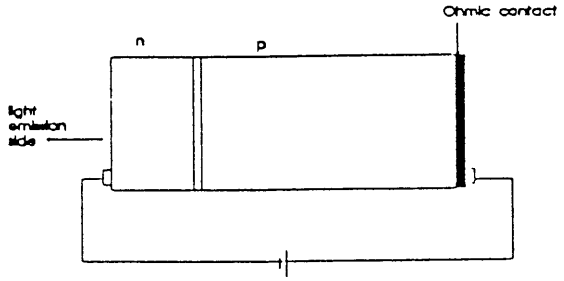


Figure 1 A forward-biased GaP diode

When the p-side GaP has oxygen doping in addition to Zn, there are certain lattice sites where Zn and oxygen atoms are nearest neighbors (see Figure 2 for details). Zn is an acceptor. O is a deep donor. Zn-O pair is neither donor nor acceptor, it is neutral.

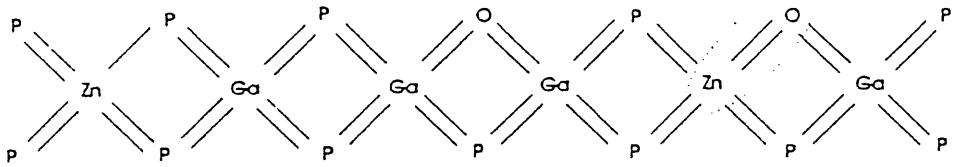


Figure 2 Zn,O doping combinations

Figure 3 shows the location of these energy levels in the forbidden gap of GaP (E_g = 2.24 eV).

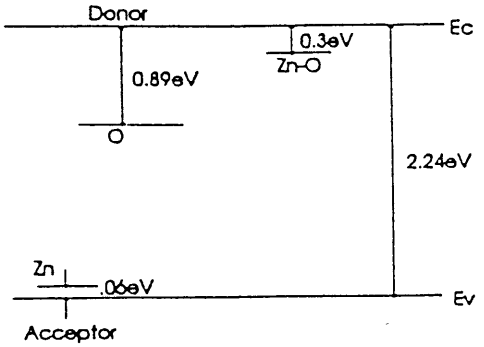


Figure 3 Energy levels in GaP: Zn-O system

Mechanism of exciton formation: The injected electrons (from the n-side into the p-side) travel in the conduction band. However, in the real space they encounter (besides the GaP lattice) Zn acceptors, O donors, and Zn-O neutral complexes. Some of these injected electrons become trapped at the Zn-O sites. After trapping, Zn-O sites become negatively charged, and in turn holes (majority carriers on the p-side) get bound via coulombic attraction to these electrons. This process is called exciton formation. Note that there is no net charge on an exciton. The exciton can be thought of as a hydrogen-like state with electron revolving around a positively charged hole.

The binding energy of an exciton ranges from 0.004 eV to 0.04 eV. In general the exciton binding energy E_{ex} is:

$$E_{ex}=\frac{m_r q^4}{8\epsilon_o^2\epsilon_r^2 h^2} \tag{1}$$

Here m_r = reduced watts of the exciton, $\frac{1}{m_r}=\frac{1}{m_h}+\frac{1}{m_e}$

q = electron charge
ϵ_r = dielectric constant of GaP
h = Plank's constant

Binding energy can also be viewed as the dissociation energy. The later being the energy needed to make the electron and hole free, overcoming the coulombic attraction.

Excitonic decay and photon emission: When the electron and hole forming an exciton recombine, this recombination results in photon emission. The probability of photon emission is as high (if not higher) as in the case of direct transitions.

The energy of photon $h\nu$ emitted upon the decay of an exciton at the Zn-O site is:

$$h\nu = E_g - 0.3 - E_{ex} \tag{2}$$

For example, if E_{ex} = 0.04 eV

$$h\nu = 2.24 - 0.3 - .04 = 1.9eV$$

or $h\nu$ = 0.65 μm or 6500Å.

Exciton decay and photon emission involving phonons (OPTIONAL)
Sometimes the excitonic decay is associated with either phonon absorption or emission.

$$h\nu = E_g - 0.3 - E_{ex} \pm E_p \tag{3}$$

Here E_p is the phonon energy: $+E_p$ for phonon absorption, and $-E_p$ for phonon emission.

GaP: N System (Green LEDs)

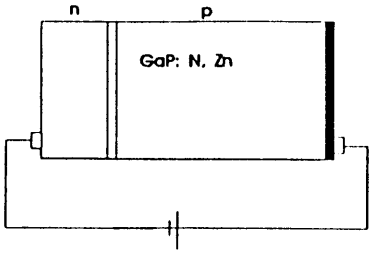


Figure 4 A GaP LED emitting green light

In this case the p-side of GaP is doped both with Zn as well as nitrogen. Nitrogen is pentavalent like phosphorus, therefore, the substitution of a phosphorus atom by a nitrogen atom does not create a donor or an acceptor. However, the addition of N introduces a neutral energy level 0.08 eV below the conduction band edge. This is shown in Figure 5.

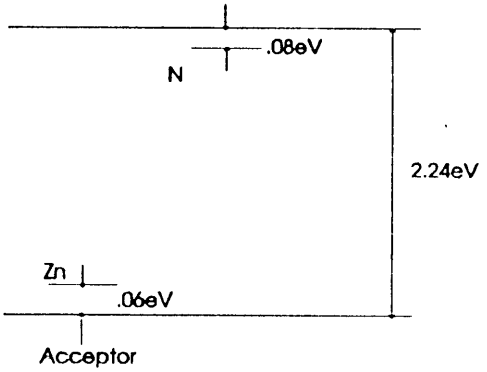


Figure 5 Energy levels in a GaP:N,Zn system

Exciton formation: An injected electron gets trapped at the nitrogen level, and subsequently binds a hole to form an exciton.

The decay of this exciton results in a photon emission. The energy of the photon is

$$h\nu = E_g - 0.08 - E_{ex}$$

The electron-hole recombination via excitonic decay is almost like a vertical (direct) transition.

If E_{ex} = 0.004eV

$$h\nu = 2.24 - .08 - .004 = 2.156eV$$

$$\lambda = \frac{1.24}{2.156} = 0.575\mu m = 5750\text{Å}$$

Light Emission Efficiency

We have studied various types of transitions leading to photon emission when injected electrons recombine with majority holes in a forward-biased n-p junction. It should be pointed out that not all recombinations lead to radiative transitions. Depending on the material, there is always a finite probability of nonradiative transitions (without photon emission). However, once a photon is generated we would like to extract it with minimal loss. This is treated under light extraction efficiency. The efficiency can be understood in two parts -- internal efficiency and external efficiency

Internal efficiency η_{int} is made up of two components

(1) quantum efficiency η_q

(2) injection efficiency η_{inj}

$$\eta_{int} = \eta_q \cdot \eta_{inj}$$

(1) η_q : η_q is determined by the probability of a radiative or nonradiative transition once an EHP (electron hole-pair) recombines. The internal quantum efficiency (η_q) is defined as the number of photons generated per injected electron.

$$\eta_q = \frac{\frac{1}{\tau_r}}{\frac{1}{\tau}}$$

$$\frac{1}{\tau} = \frac{1}{\tau_r} + \frac{1}{\tau_{nr}}$$

$$\eta_q = \frac{\tau_{nr}}{(\tau_{nr} + \tau_r)} \qquad (4)$$

τ = effective lifetime

τ_r = lifetime of an excess carrier which recombines radiatively

τ_{nr} = lifetime of an excess carrier which recombines nonradiatively

For $\eta_q \gg 1$, we need $\tau_{nr} \gg \tau_r$; i.e. the lifetime of the nonradiative process should be much higher than the radiative process.

(2) Injection efficiency η_{inj}

$$\eta_{inj} \sim \frac{I_n(x_p)}{I_n(x_p)+I_p(-x_n)} = \frac{\left(\frac{qAD_n n_{po}}{L_n}\right)\left(e^{\frac{qV_f}{kT}}-1\right)}{\left(\frac{qAD_n n_{po}}{L_n}+\frac{qAD_p p_{no}}{L_p}\right)\left(e^{\frac{qV_f}{kT}}-1\right)} = \frac{\frac{(D_n n_{po})}{L_n}}{\frac{(D_n n_{po})}{L_n}+\frac{(D_p p_{no})}{L_p}} \qquad (5)$$

Extraction efficiency $\eta_{extraction}$

The extraction efficiency, by definition, is the fraction of a photon density or light intensity received from the front surface of a LED. It is comprised of several components.

(1) 50% Loss due to travel towards the back contact
Figure 6 shows that about ½ of the generated light is lost as it travels towards the back electrode. Note that the wafer thickness is very small as compared to its lateral dimensions.

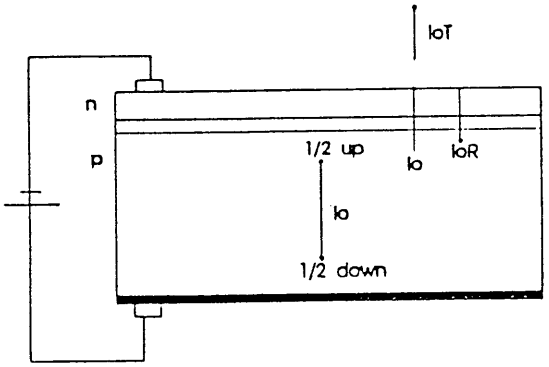


Figure 6 Photon loss mechanisms (#1 and #2).

(2) Front surface reflection
The light ray incident on the front surface has finite reflectivity. Assuming normal incidence, the transmitted fraction

$$T = \frac{4n_r}{(1+n_r)^2}$$

Here, n_r is the index of refraction of the LED material relative to air.

(3) Internal loss due to total reflection

The light is generated in a medium having a higher index of refraction than air. Therefore, rays having an angle of incidence greater than θ_c (critical angle) are reflected back internally. In otherwords light incident in a cone of apex angle θ_c is transmitted out. This is illustrated in Figure 7.

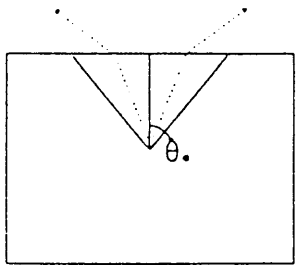


Figure 7 A schematic representation of loss due to total internal reflection.

Derivation:

Snell's Law states

$$\frac{\sin i}{\sin r}=\frac{1}{n_r} \quad or, \quad \frac{\sin\theta_c}{\sin\frac{\pi}{2}}=\frac{1}{n_r} \qquad \theta_c=\sin^{-1}\left(\frac{1}{n_r}\right) \tag{6}$$

Here n_r is the index of refraction of the semiconductor. The fraction of light transmitted is given by

$$T=1-\cos\theta_c=1-(1-\sin^2\theta_c)^{\frac{1}{2}}=1-\left(1-\frac{1}{n_r^2}\right)^{\frac{1}{2}} \tag{7}$$

Including the light loss due to the 50% light traveling towards the back contact, front surface reflection and total internal reflection, we get

$$\eta_{extraction}=\frac{1}{2}\cdot\frac{4n_r}{(1+n_r)^2}\cdot\left[1-\left(1-\frac{1}{n_r^2}\right)^{\frac{1}{2}}\right] \tag{8}$$

External quantum efficiency η_{ext}

η_{ext} depends on η_{int} and light extraction efficiency $\eta_{extraction}$

$$\eta_{ext} = \eta_{extraction} \cdot \eta_{int}$$

$$\eta_{ext} = \left[\frac{\tau_{nr}}{\tau_{nr}+\tau_r}\right] * \left[\frac{\frac{D_n n_{po}}{L_n}}{\frac{D_n n_{po}}{L_n}+\frac{D_p p_{no}}{L_p}}\right] * \left[\frac{1}{2}\right] * \left[\frac{4n_r}{(1+n_r)^2}\right] * \left[1-\left[1-\frac{1}{n_r^2}\right]^{\frac{1}{2}}\right] \quad (9)$$

Conversion Efficiency

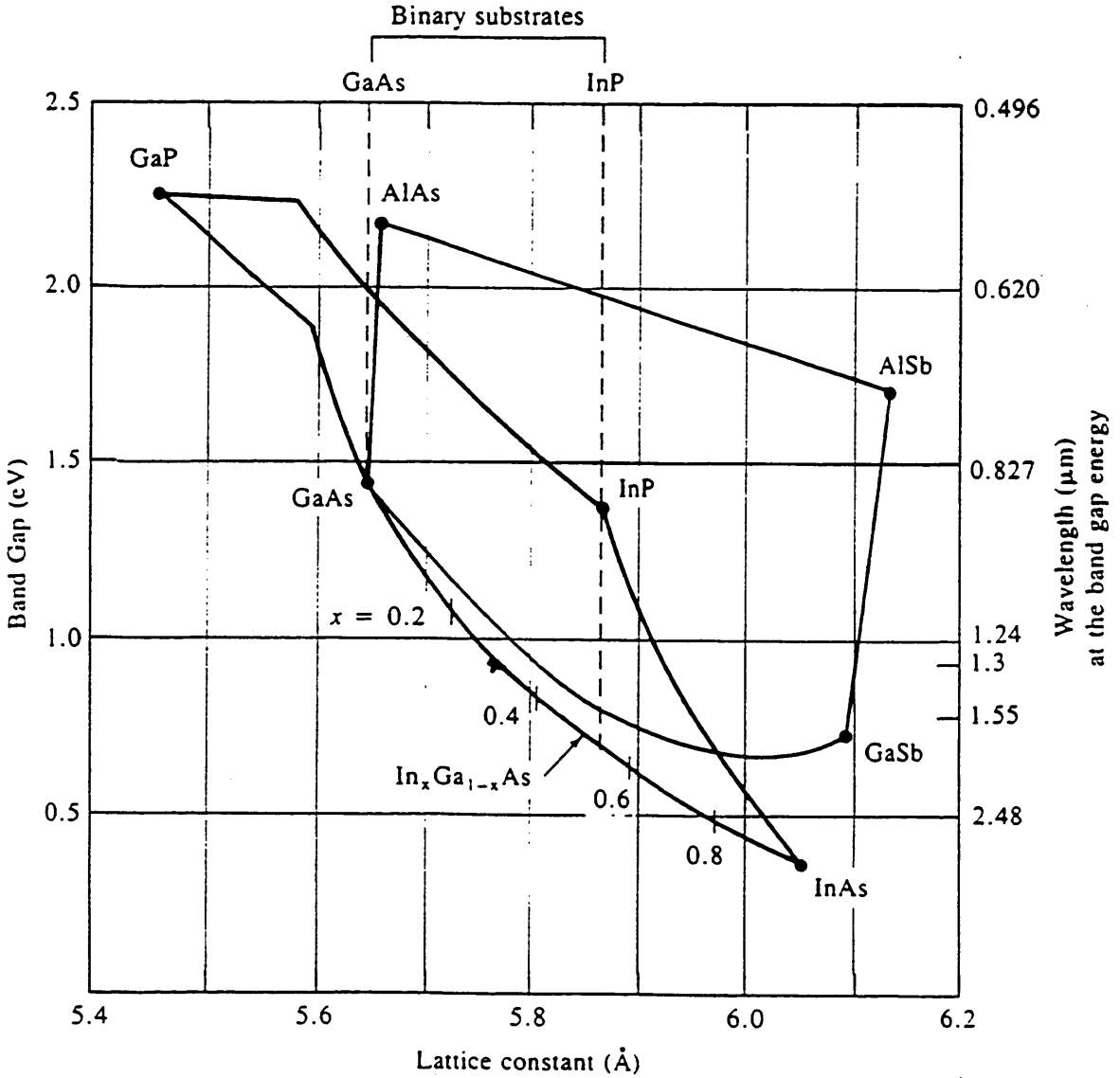
$$\eta_c = \frac{\textit{Luminous light flux per unit junction area}}{\textit{Input d.c. power per unit area} \Rightarrow J_F \cdot V_F} \tag{10}$$

Sometimes the power conversion efficiency is defined as

$$\eta_P = \frac{\int \frac{dP}{d\lambda} d\lambda}{J_F V_F} \tag{11}$$

Here, $P(\lambda)$ = light output at wavelength λ

Fig. 1-15 **Relationship between band gap and lattice constant for alloys in the InGaAsP and AlGaAsSb systems. The dashed vertical lines show the lattice constants for the commercially available binary substrates GaAs and InP. For the marked example of $In_xGa_{1-x}As$, the ternary composition x = 0.53 can be grown lattice-matched on InP, since the lattice constants are the same. For quaternary alloys, the compositions on both the III and V sublattices can be varied to grow lattice-matched epitaxial layers along the dashed vertical lines between curves. For example, $In_xGa_{1-x}As_yP_{1-y}$ can be grown on InP substrates, with resulting band gaps ranging from 0.75 eV to 1.35 eV. In using this figure, assume the lattice constant *a* of a ternary alloy varies linearly with the composition *x*.**



SOLID STATE
ELECTRONIC DEVICES, 4/E
by Ben G. Streetman

Material Composition

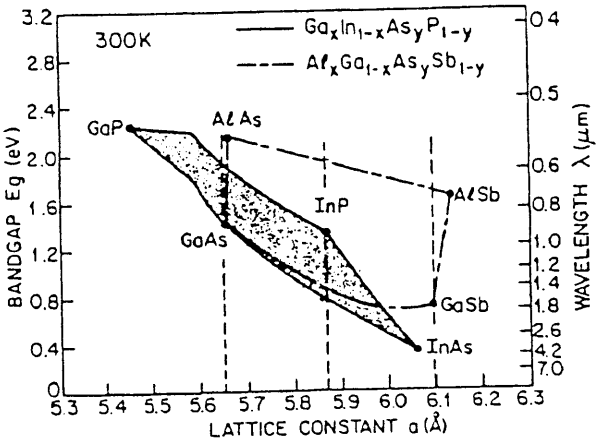
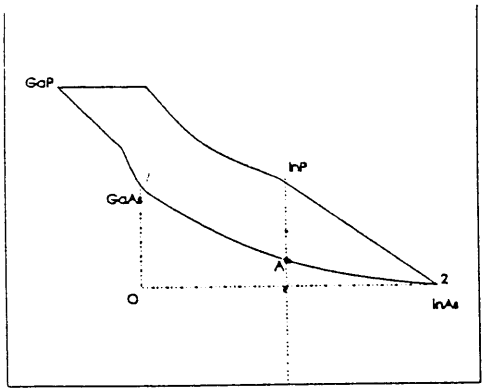


Fig. 16 Energy bandgap and lattice constant for two III–V compound solid alloy systems.[1]



Point A

$$\frac{\overline{AO}}{\overline{O2}}=0.528, \quad \frac{\overline{A2}}{\overline{O2}}=0.472$$

Therefore : $Ga_{.472}In_{.528}As$
(x = .472 1-x = .528)

Refractive Index

The compositional dependance of refractive index in the case of $Al_xGa_{1-x}As$ is given by[2]

$$n(x)=3.59-0.71x+0.091x^2 \tag{12}$$

and for $In_xGa_{1-x}As_yP_{1-y}$[3]

$$n(x,y)=3.52xy+3.39x(1-y)+3.60y(1-x)+3.56(1-x)(1-y) \tag{13}$$

---

[2]H.C. Casey Jr. & M.B. Panish, Heterostructure Lasers Part A: Fundamental Principles, Academic Press, 1978, Chapter 2

[3]G.H.Olsen et al, Journal of Electronic Materials, vol 9, pp. 977-987, 1980.

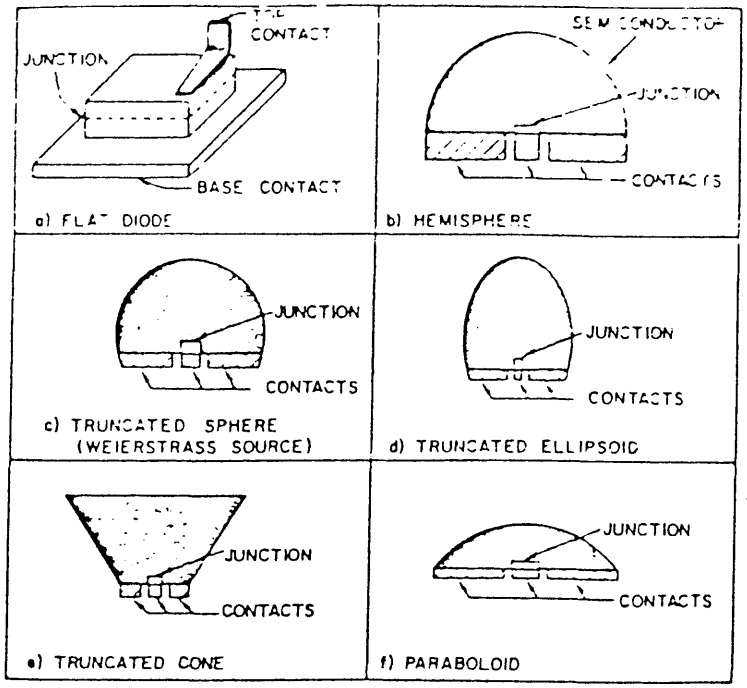


Fig. 75. LED geometries to increase the light extraction or optical efficiency [332]. The effectiveness of the various geometries is listed in Table VIII.

TABLE VIII

FIGURES OF MERIT FOR VARIOUS LED GEOMETRIES PER UNIT INTERNAL LIGHT FLUX GENERATION ($n = 3.6$)

Geometry	Radiant Flux	Maximum Radiant Intensity	Average Radiant Intensity
	P	$J(0)$ $\theta = 0$	$(J(0))$ $\theta = 26°$
Flat plane diode area emission	0.013	0.0042	0.0039
Hemisphere	0.34	0.054	0.054
Weierstrasse sphere	0.34	1.4	0.52
Truncated ellipsoid	0.25	9.8	0.39
Truncated cone	0.20	0.063	0.059
Paraboloid source			
$R_i/F_p = 0.1$	0.34	0.84	0.52
$R_i/F_p = 0.05$	0.34	3.3	0.52

Note: Table from [332].