Light-Emitting Diodes

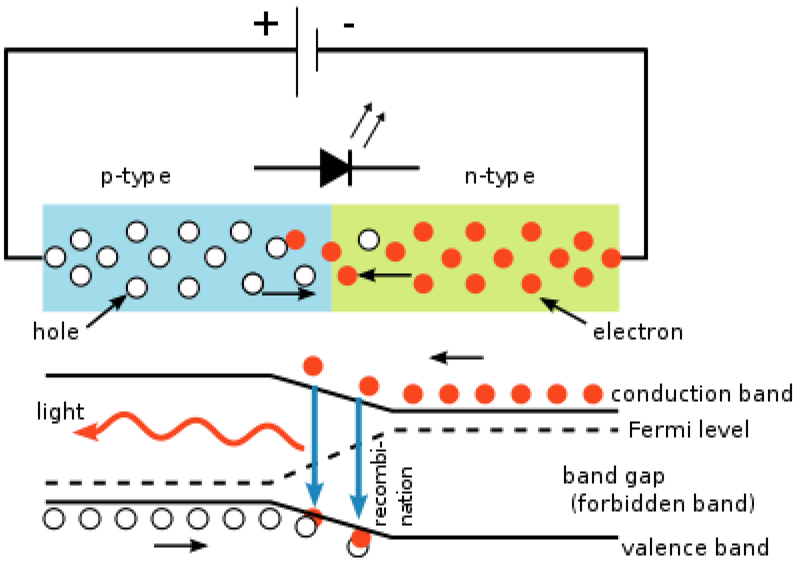
Robby Spaulding

Topics

- Radiative Recombination
- LED Structures
- Lambertian Pattern
- Temperature Dependence and Efficiency Drooping
- Element Make-up and Materials
- Lattice Parameter
- Critical Angle
- Quantum Efficiency and Optical Power

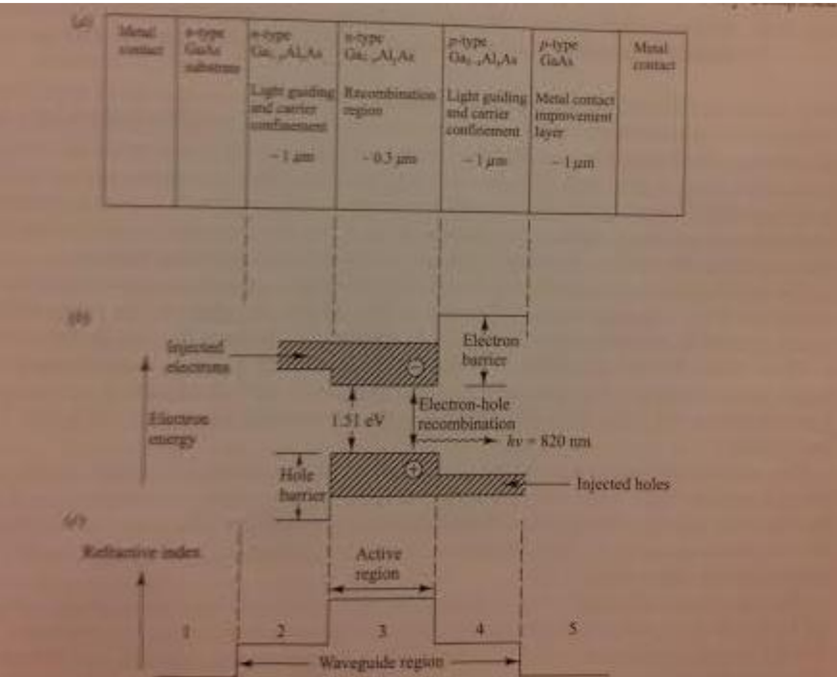
How an LED Produces Light

- Radiative Recombination occurs when an electron in the conduction band recombines with a hole in the valence band and the excess energy is emitted in the form of a photon.



LED Structures

- Double-heterostructure (heterojunction)



(a) Cross-sectional drawing (not to scale) of a typical GaAlAs double-heterostructure light emitter. In this structure, $x > y$ to provide for both carrier confinement and optical guiding; (b) energy band diagram showing the active region, and the electron and hole barriers that confine the charge carriers to the active layer; (c) variations in the refractive index; the lower index of refraction of the material in regions 1 and 5 creates an optical barrier around the waveguide region.

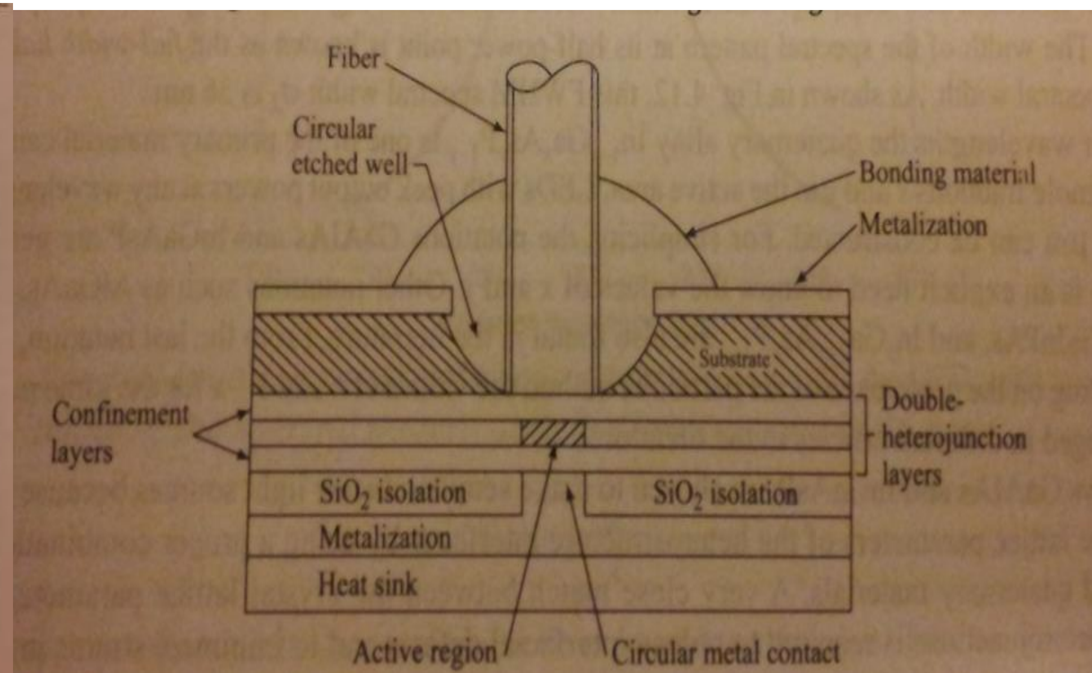


Figure: A schematic of a surface emitter with double-heterojunction layers.

Surface Emitters and Edge Emitters

- A surface emitter is also know as a Burrus or front emitter.

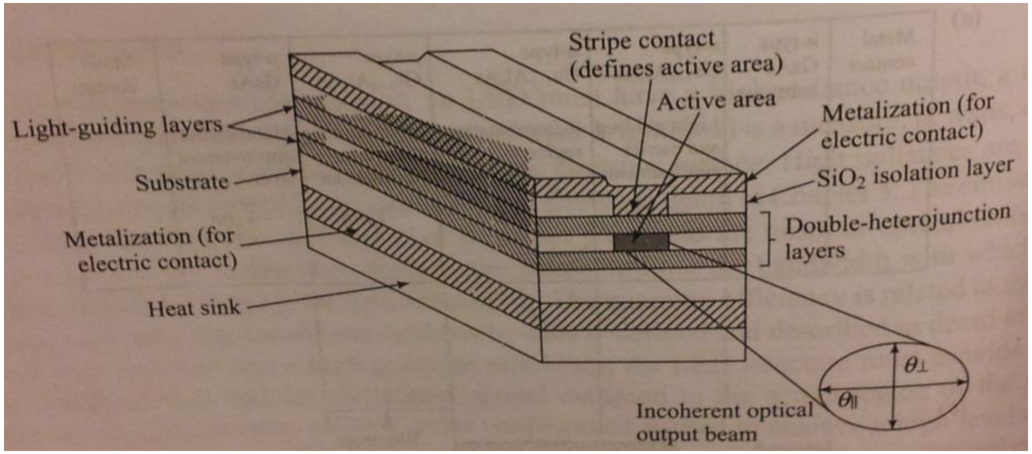


Figure: Schematic of an edge-emitting double-heterojunction LED. The output beam is lambertian in the plane of the pn junction (θII= 120°) and highly directional perpendicular to the pn junction (θ⊥=30°)

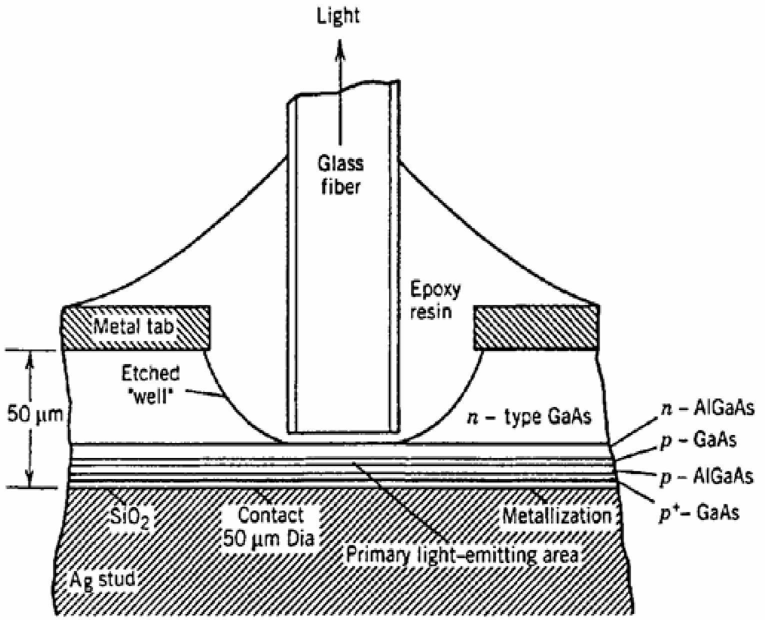
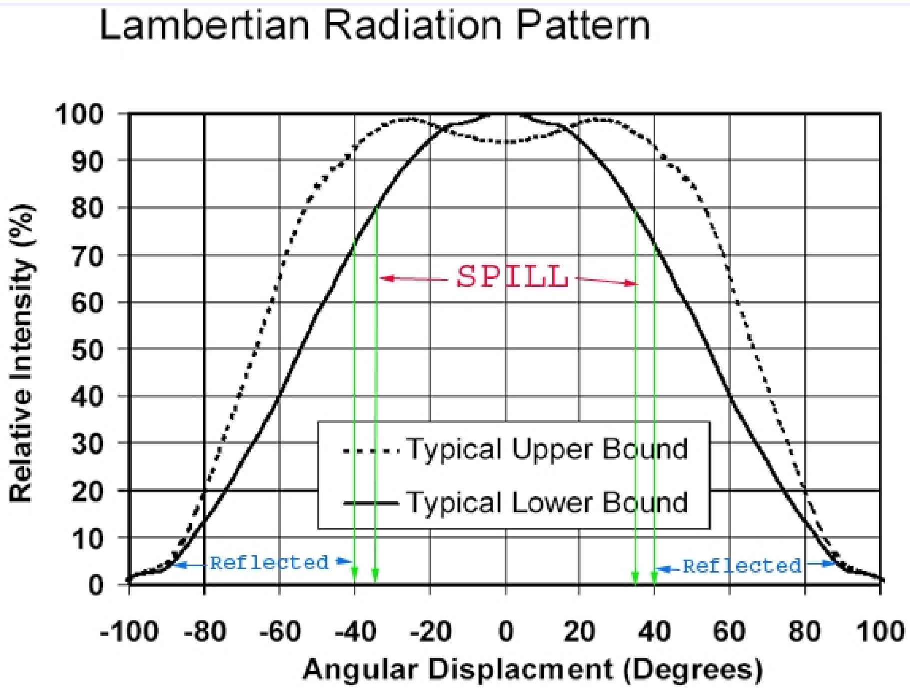


Figure 3.22: Schematic of a surface-emitting LED with a double-heterostructure geometry.

Lambertian Pattern

- Lambertian pattern – An isotropic emission pattern with a 120° half-power beam width



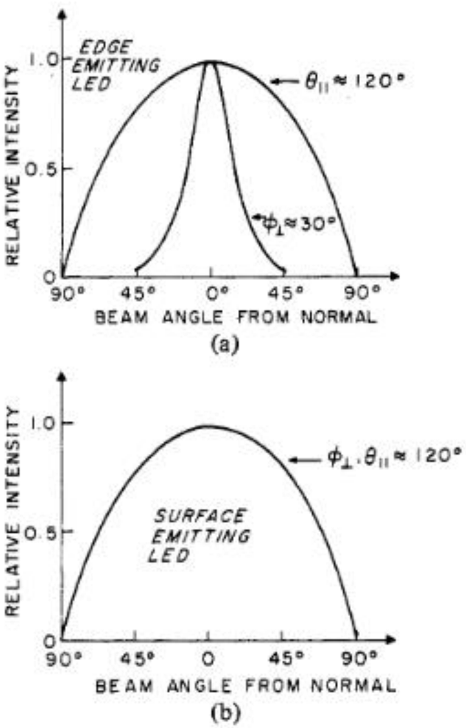
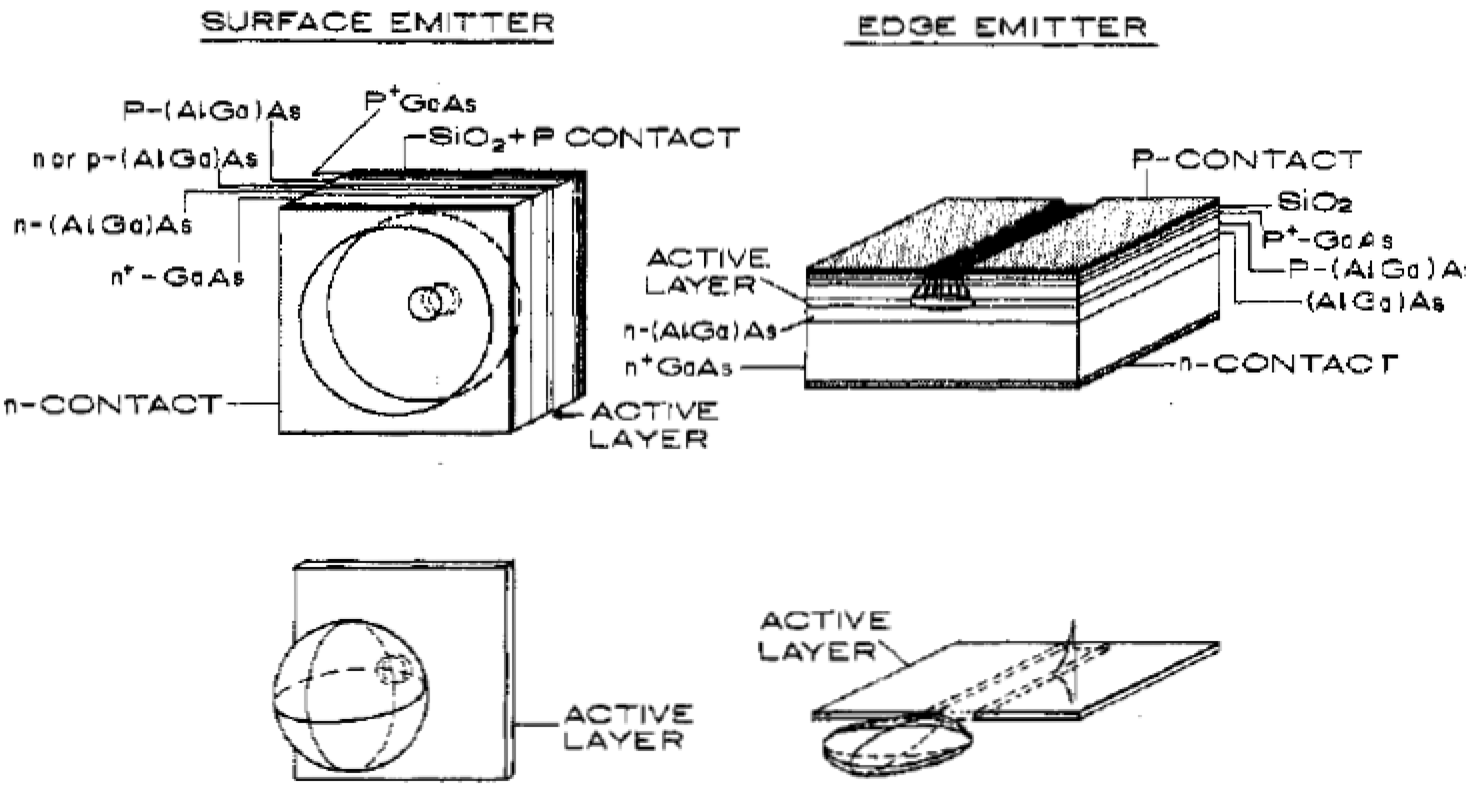


Fig. 4. Typical far-field intensity patterns in the junction plane ($\theta_{\parallel}$) and in a plane perpendicular to the junction ($\phi_{\perp}$) for: (a) very-high-radiance edge emitters [3]; (b) surface emitters.

Surface Emitters and Edge Emitters



EMITTED LIGHT ANGULAR DISTRIBUTIONS

Temperature Dependence and Efficiency drooping

- Toshiba has produced LEDs with an operating temperature range of -40 to 100 °C.
- The luminous efficacy of LEDs decreases as the electrical current increases. Heating also increases with higher currents which compromises the lifetime of the LED. These effects put practical limits on the current through an LED in high power applications.
- Efficiency droop is a flaw in LED lightbulbs that causes efficiencies to drop by as much as 20% when the LEDs are subjected to greater electrical currents

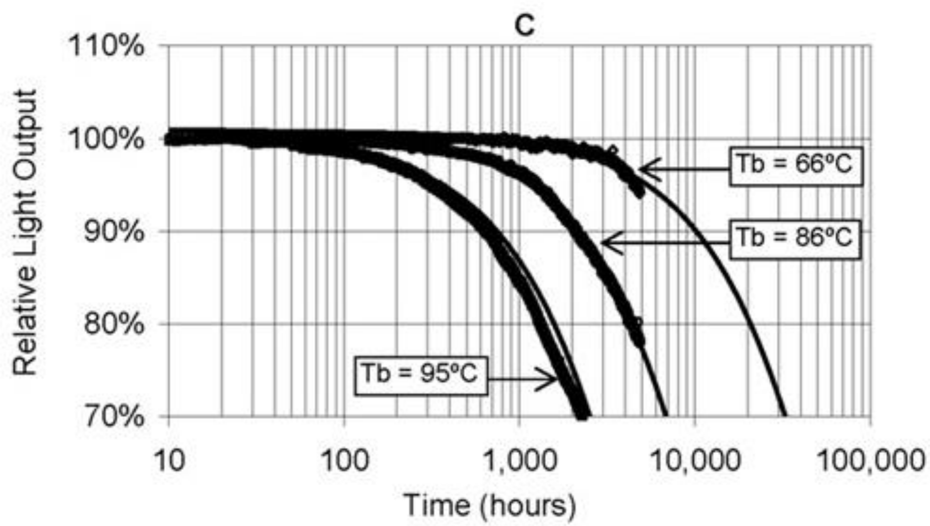


Figure 1: The effect of board temperature on white LED lifetime. (Courtesy of the Lighting Research Center.)

Light Source Materials

- Only in direct-bandgap material is the radiative recombination sufficiently high to produce an adequate level of optical emission.
- None of the normal single-element semiconductors are direct-gap materials, many binary compounds are.
- Group III –(e.g. Al, Ga, or In)
- Group V – (e.g. P, As, or Sb)

Managing Wavelengths

- Various ternary and quaternary combinations of these elements are also direct-gap materials.
- The ratio x of aluminum arsenide to gallium arsenide determines the bandgap of the alloy and the wavelength of the peak emitted radiation.

$E = hv = hc/\lambda$ E - Energy v - Frequency λ - Peak Emission Wavelength

h - Planck's Constant ($6.62606957 \times 10^{-34}$ m^2 kg/s)

c - Speed of Light (299,792,458 m/s)

$\lambda(\mu m) = 1.240/Eg\ (eV)$ Eg – Bandgap Energy

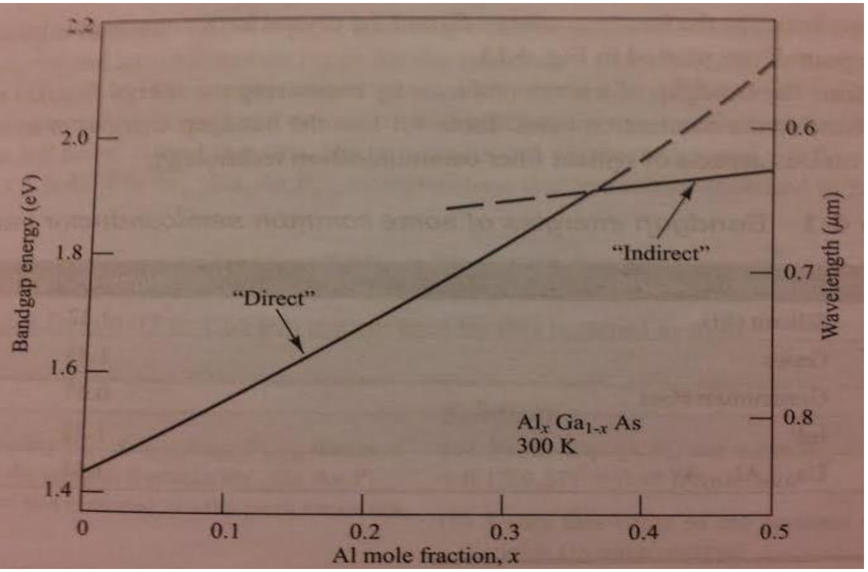


Figure: Bandgap energy and output wavelength as a function of aluminum mole fraction x for Al(x)Ga(1-x) at room temperature.

Group	Material	Symbol	Band gap (eV) @ 302K
IV	Diamond	C	5.5
IV	Silicon	Si	1.11
IV	Germanium	Ge	0.67
III–V	Gallium(III) nitride	GaN	3.4
III–V	Gallium(III) phosphide	GaP	2.26
III–V	Gallium(III) arsenide	GaAs	1.43
IV–V	Silicon nitride	Si_3N_4	5
IV–VI	Lead(II) sulfide	PbS	0.37
IV–VI	Silicon dioxide	SiO_2	9
	Copper(I) oxide	Cu_2O	2.1

Lattice Parameters

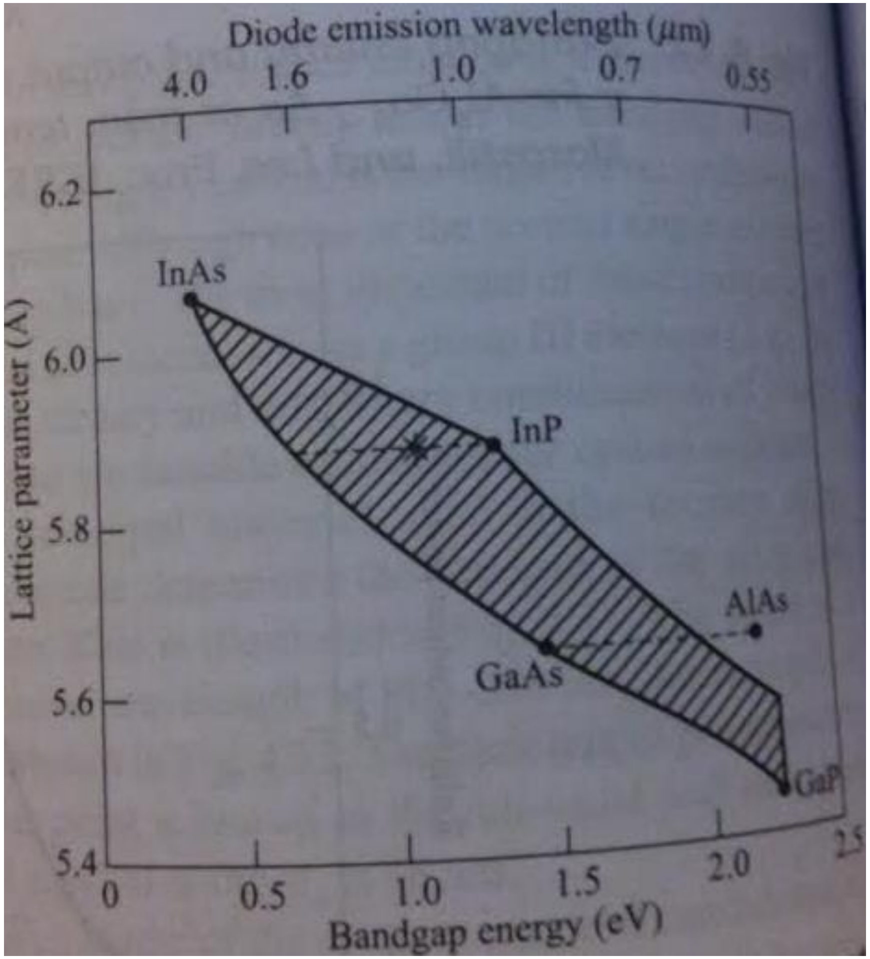


Figure: The shaded area is for the quaternary alloy InGaAsP. The asterisk is for In(0.8)Ga(0.2)As(0.35)P(0.65) (Eg = 1.1 eV) lattice-matched to InP.

- A heterojunction with matching lattice parameters is created by choosing two material compositions that have the same lattice constant but different bandgap energies (the bandgap differences are used to confine the charge carriers).
- Quaternary alloy In(1-x)Ga(x)As(y)P(1-y) is used for wavelengths between 1.0 and 1.7 μm.

Critical angle

- At the interface of a material boundary only that fraction of light falling within a cone defined by the critical angle Φc will cross the interface.
- $\Phi c = 1/\sin(n(2)/n(1))$ where $n(1)$ is the refractive index of the semiconductor and $n(2)$ is the refractive index of the outside material.

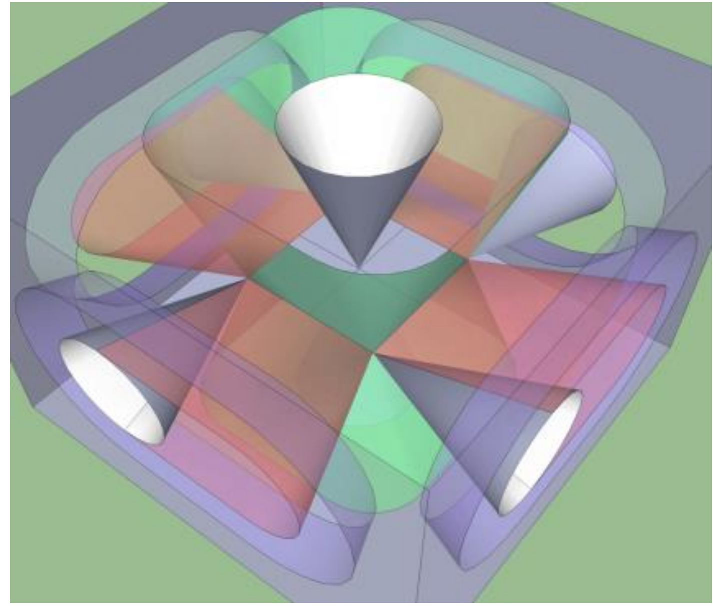


Figure: The light emission cones of a real LED wafer are far more complex than a single point-source light emission. The light emission zone is typically a two-dimensional plane between the wafers. Every atom across this plane has an individual set of emission cones. Drawing the billions of overlapping cones is impossible, so this is a simplified diagram showing the extents of all the emission cones combined.

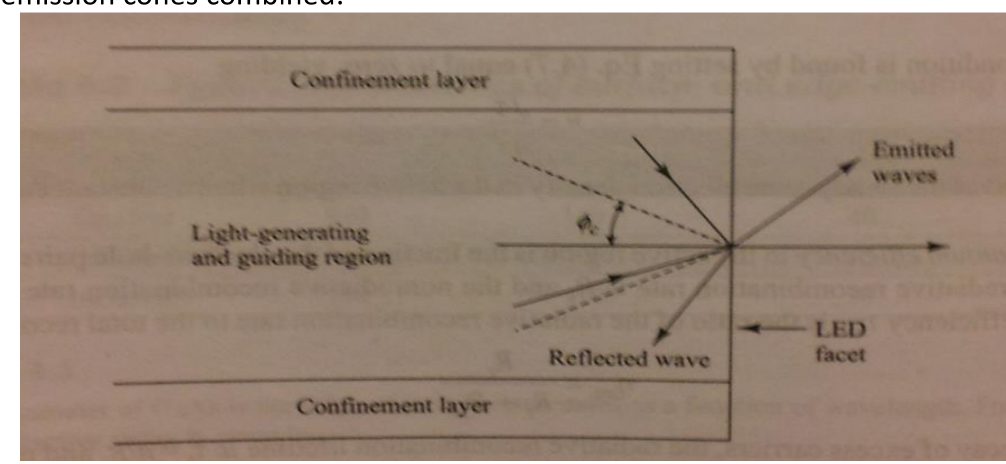
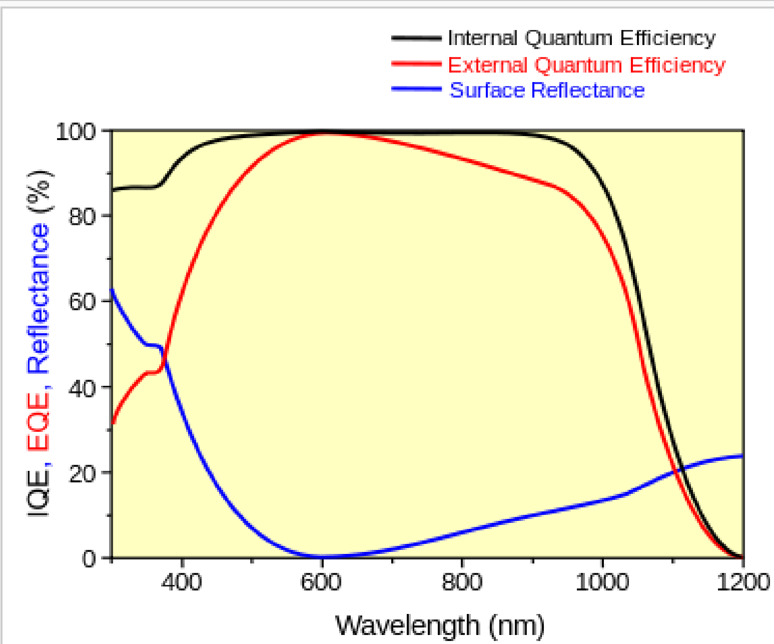


Figure: Only light falling within a cone define by a critical angle Φc will be emitted from an optical source.

Quantum Efficiency and Optical Power

- **External Quantum Efficiency –** The ratio of the photons emitted from the LED to the number of internally generated photons.
- **Internal Quantum Efficiency –** the fraction of the electron-hole pairs that recombine radiatively in the active region.
- Optical Power=(EQE)(Power Internal)



A graph showing variation of internal quantum efficiency, external quantum efficiency, and reflectance with wavelength of a crystalline silicon solar cell.

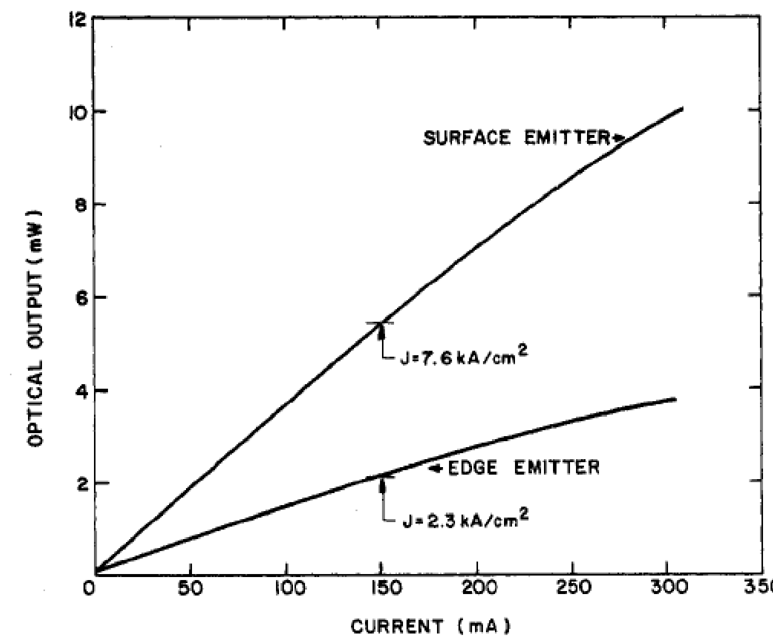


Fig. 6. Output optical power versus dc drive current for typically good surface and edge emitters. The surface emitters have 50-μm-diameter dot contacts and the edge emitters have 65-μm wide stripe contacts of 100-μm length.