Semiconductor Lasers

- Laser diode is similar in principle to an LED.

- What added geometry does a Laser diode require?

  An optical cavity that will facilitate feedback in order to generate stimulated emission.

Fundamental Laser diode: 1. Edge emitting LED. Edge emission is suitable for adaptation to feedback waveguide.

2. Polish the sides of the structure that is radiating.

3. Introduce a reflecting mechanisn in order to return radiation to the active region.

4.Drawback: low Q due to excessive absorption of radiation in p and n layers of diode.

   Remedy: Add confinement layers on both sides of active region with different refractive indexes.Radiation will reflect back to active region.
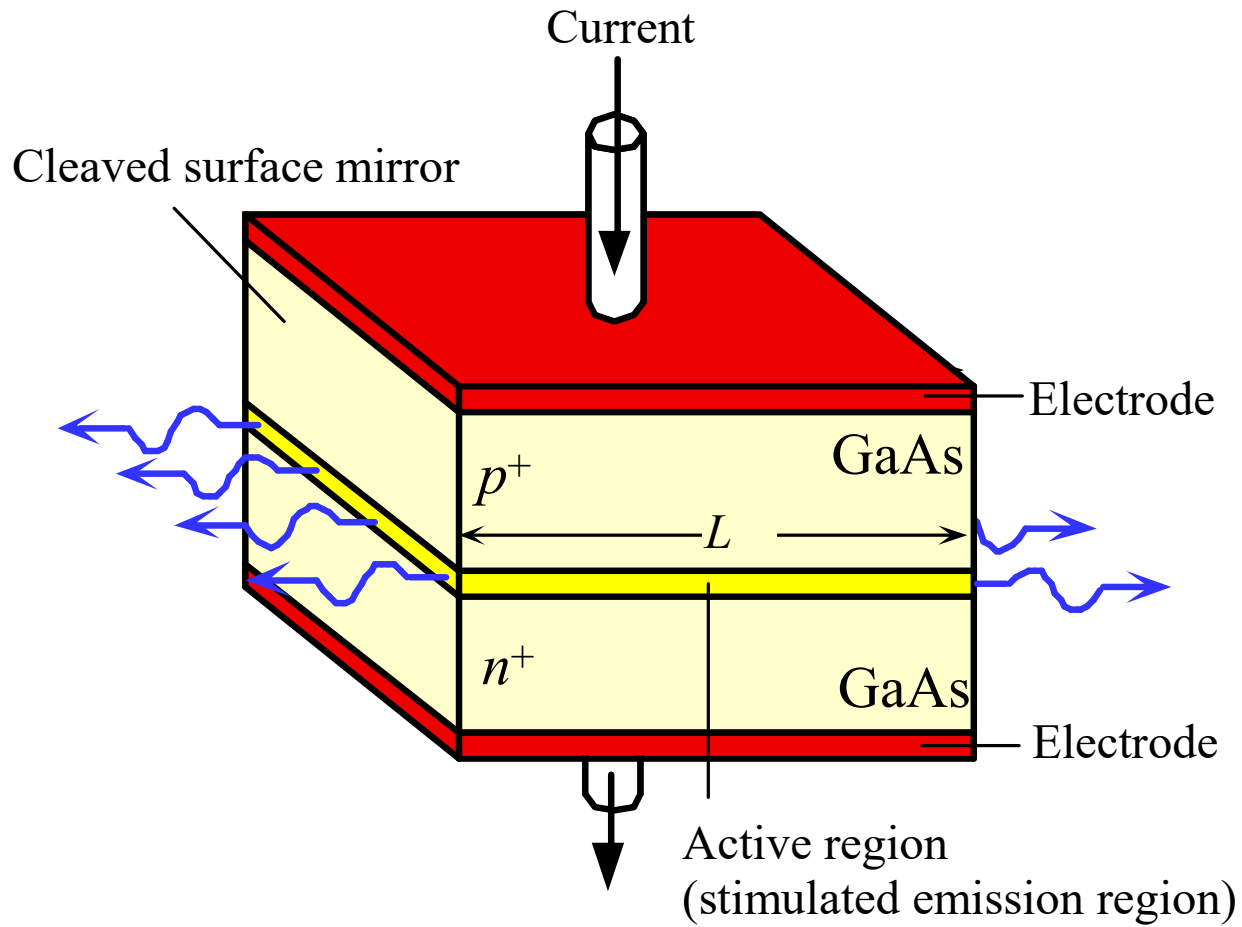
Laser Diodes

5. Polishing of the emitting sides of the cavity. A considerable percentage of the radiation is reflected back alone from the difference in reflective indexes of the air-AlGaAs interface. Therefore mirror coating not necessary.

Note: radiation propagates from both sides of the device.

What function can a photodiode provide in the process?

It is attached to the inactive side to serve as a sensor for the power supply in order to provide an element of control of the laser output.

Current

Cleaved surface mirror

Electrode

GaAs

p^+

L

n^+

GaAs

Electrode

Active region
(stimulated emission region)

A schematic illustration of a GaAs homojunction laser
diode. The cleaved surfaces act as reflecting mirrors.

Laser Diodes

- Lasing occurs when the supply of free electrons exceeds the losses in the cavity.
- Current through the junction and the electron supply are directly proportional. I_{TH} must be exceeded before laser action occurs.
- Drawback of laser diode: Temperature coefficient.Threshold current increases with temperature. Possible shutdown.

   Remedy:1. Cooling mechanism. (cooling mount)

   2. Constant current power supply with photodetector.
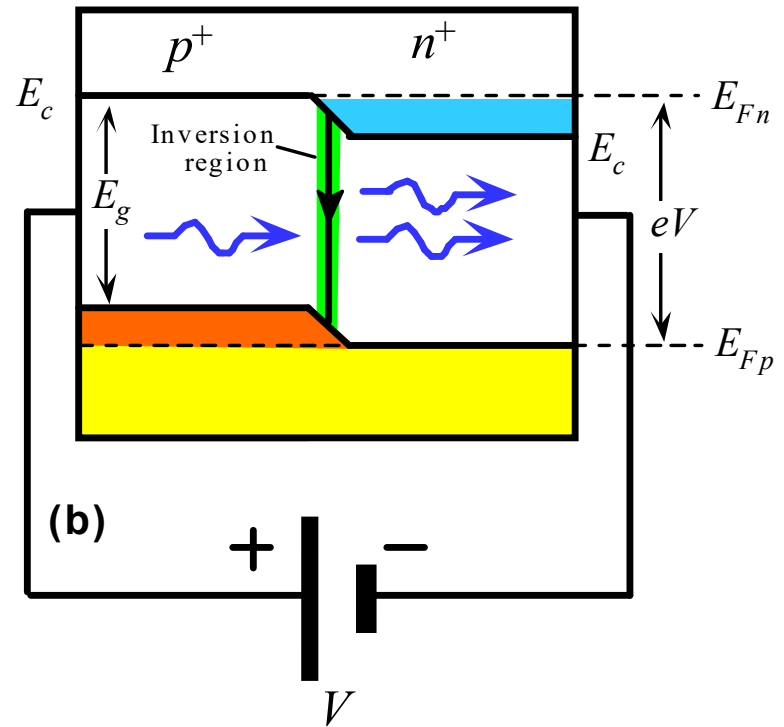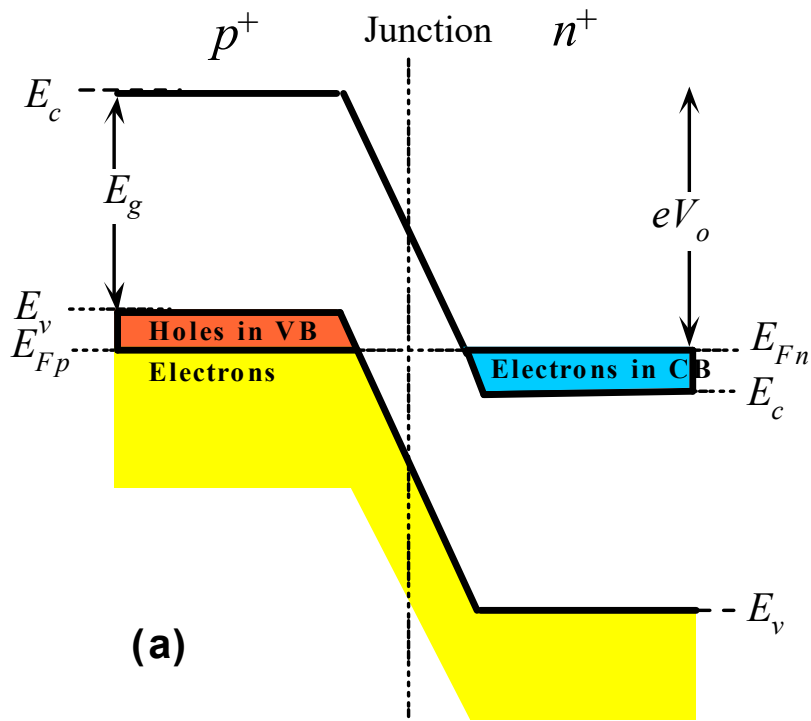
Laser Diode Action (intrinsics)

Refer to diagram of degenerately doped direct bandgap semiconductor pn junction.

Degenerate doping- where fermi level is (E_{FP}) on P-side is in the valence band (VB)and E_{FN} on the N-side is in the conduction band (CB).

$\Rightarrow$ Energy levels up to the the fermi level are occupied by electrons.

$\Rightarrow$ When there is no applied voltage the fermi level is continuous across the diode ($E_{FP} = E_{FN}$)

.

The energy band diagram of a degenerately doped *p-n* with no bias. (b) Band diagram with a sufficiently large forward bias to cause population inversion and hence stimulated emission.

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Laser Diode (intrinsics)

$\Rightarrow$ Space charge layer (SCL) is very narrow.

$\Rightarrow$ Vo (built in voltage) prevents electrons in CB (n+-side) from diffusing into CB of p+-side.

$\Rightarrow$ There is a similar barrier preventing hole diffusion from p+ to n+ sides.

$\Rightarrow$ Assuming an applied voltage (ev) greater than the bandgap energy, E_{FN} and E_{FP} are now separated by ev.

$\Rightarrow$ eV diminishes barrier potential to 0 allowing electrons to flow into SCL and over to p+-side to establish diode current.

Laser Diodes (intrinsics)

$\Rightarrow$ A similar reduction in barrier potential for holes from p+-side to n+-side occurs.

$\Rightarrow$ Result $\rightarrow$ SCL no longer depleted.
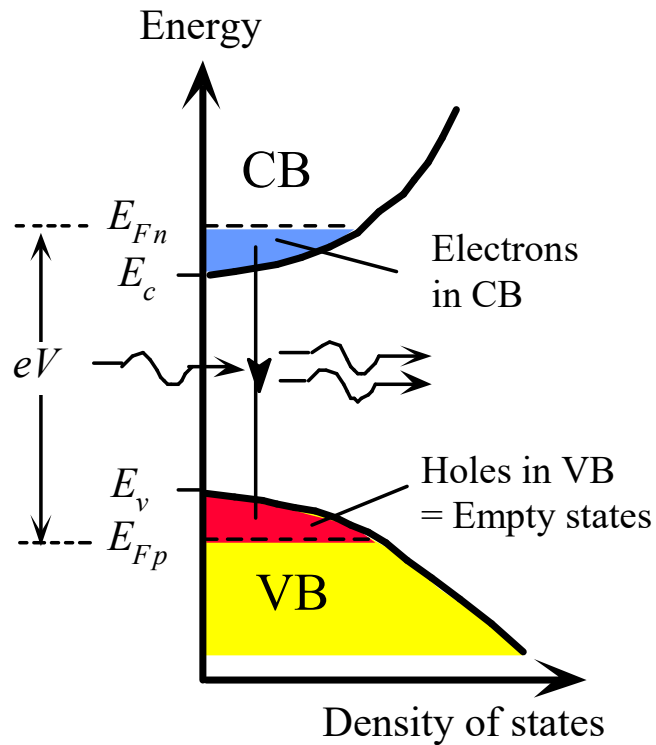
$$E_{FN} - E_{FP} = eV > Eg$$

Laser Diode (Population Inversion)
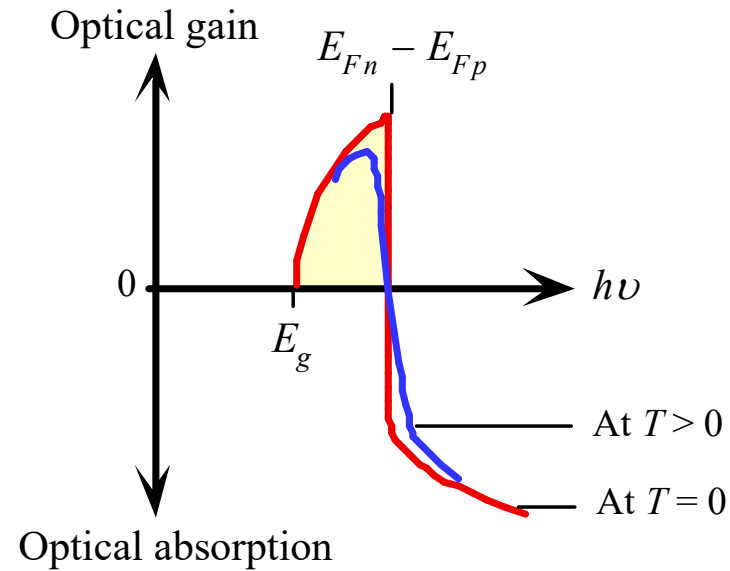
Refer to Density of States.

$\Rightarrow$ More electrons in the CB at energies near Ec than electrons in VB near Ev.

$\Rightarrow$ This is the result of a ***Population Inversion*** in energies near EC and EV.

$\Rightarrow$ The region where the population inversion occurs develops a layer along the junction called an ***inversion layer*** or ***active region***.

(a) The density of states and energy distribution of electrons and holes in the conduction and valence bands respectively at $T \approx 0$ in the SCL under forward bias such that $E_{Fn} - E_{Fp} > E_g$. Holes in the VB are empty states. (b) Gain vs. photon energy.

Laser Diode (stimulated emission)

An incoming photon with energy of $E_C - E_V$ will not see electrons to excite from E_V to E_C due to the absence of electrons at E_V .

The photon can cause an electron to fall down from E_C to E_V .

The incoming photon is stimulating ***direct recombination***.

Laser Diode (stimulated emission)

$\Rightarrow$ The region where there is more stimulated emission than absorption results in Optical gain.

$\Rightarrow$ Optical gain depends upon the photon energy and thus wavelength (see density of states).

Summary:

*Photons with energy > Eg but $< E_{FN} - E_{FP} (eV)$ cause stimulated emission.

*Photons with energy > $E_{FN} - E_{FP} (eV)$ are absorbed.

Laser Diode (pumping)

What is the impact of a temperature increase on Photon energy?

The Fermi-Dirac function spreads the energy distributions of electrons in the CB to above E_{FN} and holes below E_{FP} in the VB.

Result: a reduction in optical gain.

*Optical gain depends on $E_{FN} - E_{FP}$ which depends on applied voltage. In turn this depends on diode current.
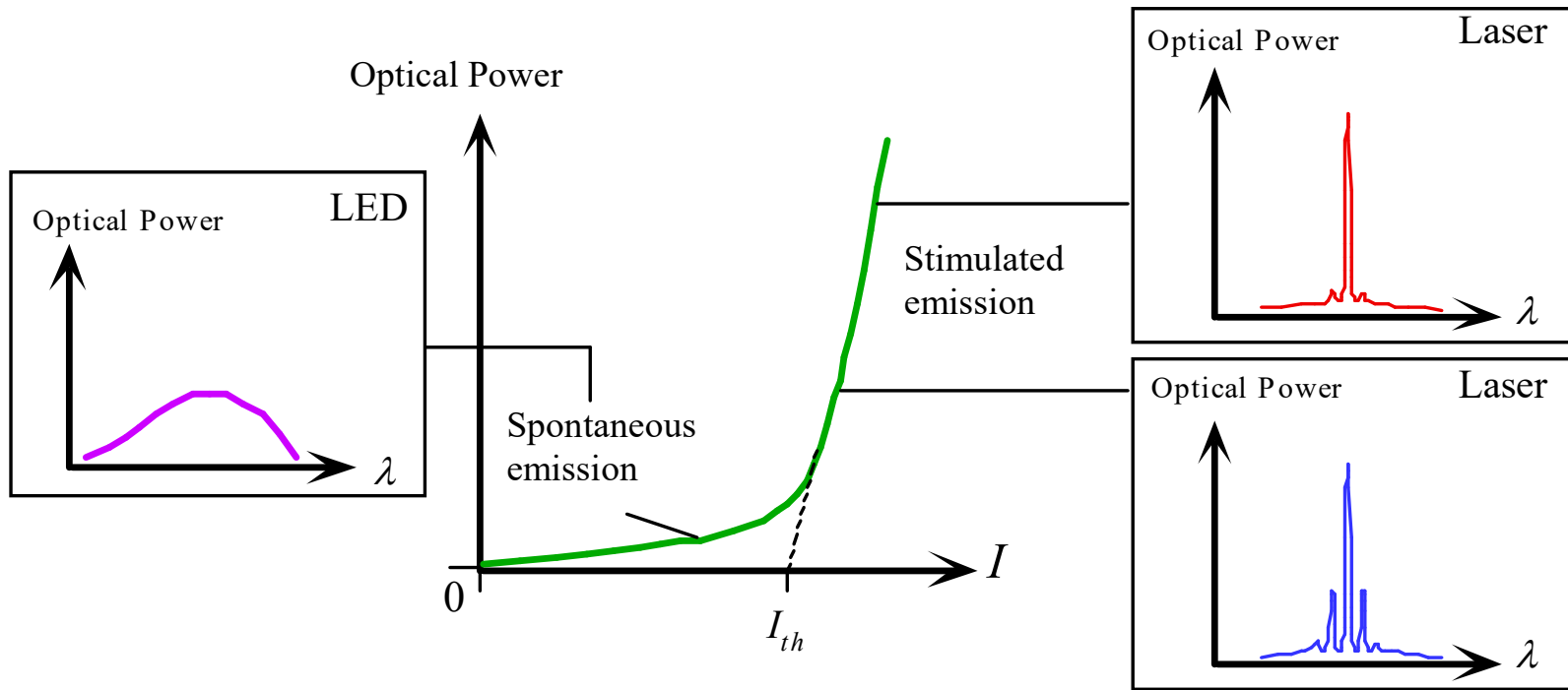
Laser Diode (pumping)

An adequate forward bias is required to develop injection carriers across a junction to initiate a population inversion between energies at E_C and energies at E_V .

What is the pumping mechanism used to achieve this?

  Forward diode current.

The process is called ***injection pumping.***

Typical output optical power vs. diode current (I) characteristics and the corresponding output spectrum of a laser diode.

Laser Diode (optical cavity)

In addition to population inversion *laser oscillation* must be sustained.

$\Rightarrow$ An optical cavity is implemented to elevate the intensity of stimulated emission. (*optical resonator*)

$\Rightarrow$ Provides an output of continuous **coherent radiation**.

$\Rightarrow$ A *homojunction* laser diode is one where the pn junction uses the same direct bandgap semiconductor material throughout the component (ex. GaAs) See slide 3.

Laser Diode (optical cavity)

The ends of the crystal are cleaved to a flatnessand the ends polished to provide reflection.

$\Rightarrow$ Photons reflected from cleaved surface stimulate more photons of the same frequency.

$\Rightarrow$ The λ of radiation that escalates in the cavity is dependant on the length L of the cavity.(resonant length)

$\Rightarrow$ Only multiples of ½ λ exist.

$$m \times \frac{\lambda}{2n} = L \; where : m \; is \; an \, \text{integer (mode or resonant frequency)}$$

n is the refractive index of the semiconductor

λ is the free space wavelength

$$m \frac{\lambda}{2n} = L \ where : m \ is \ an \ \text{integer (mode or resonant frequency)}$$

n is the refractive index of the semiconductor

λ is the free space wavelength

$$\delta\lambda_m = \frac{\lambda^2}{2nL}$$

LaserDiode (modes)

Separation between the potential modes that can develop, or allowed wavelengths, can be determined by the equation in the previous slide as $\Delta\lambda_m$.

=>the output spectrum of the laser diode depends upon the nature of the optical cavity and optical gain versus wavelength.

Note: lasing radiation occurs when optical gain in the medium can overcome photon losses from the cavity which requires diode current to exceed a threshold current   .

Light that exists below I_{th} is due to spontaneous emission.

Incoherent photons are emitted randomly and device behaves like an LED.

Laser Diodes(output)

Lasing oscillations occur when optical gain exceeds photon losses and this is where optical gain reaches threshold gain at I_{th} .

- This is the point where modes or resonant frequencies resonate within the cavity.

- The polished cavity ends are not perfectly reflecting with approximately 32% transmitting out of cleaved ends.

- The number of modes that exist in the output spectrum and their magnitudes depend on the diode current.

Laser Diodes (heterostructure)

The drawback of a homojunction structure is that the threshold current density (J_{th}) is too high and therefore restricted to operating at very low temperatures.

Remedy: Heterostructure semiconductor laser diodes.
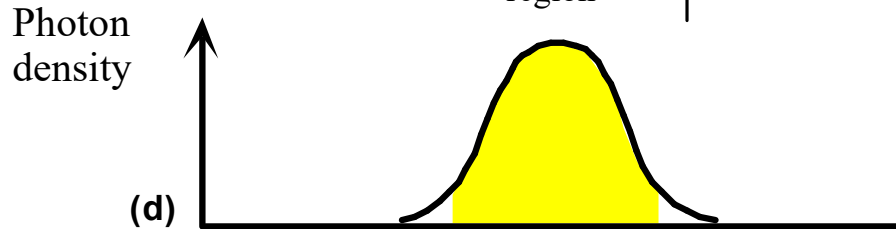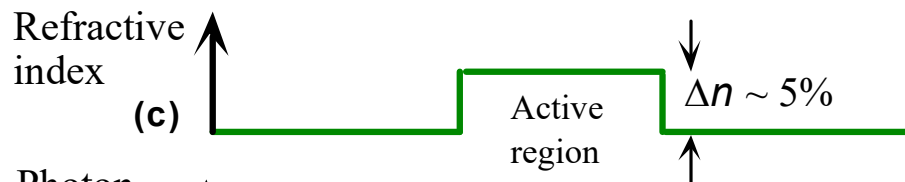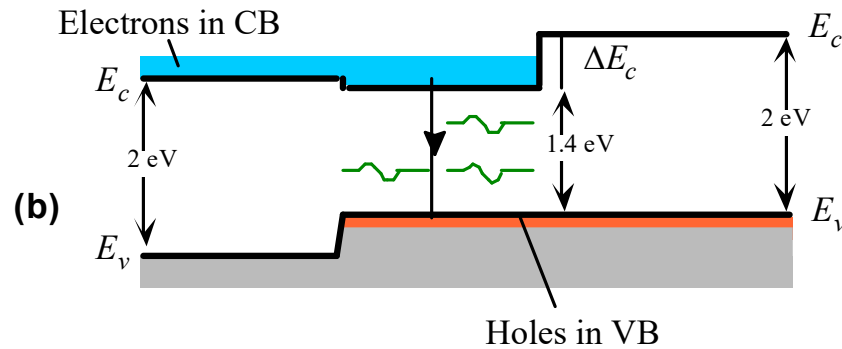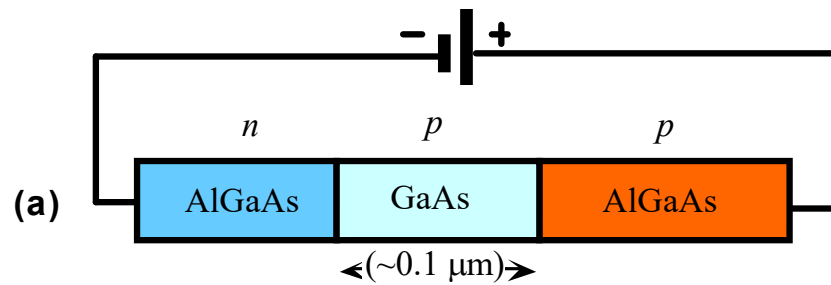
What must be accomplished?

- to reduce threshold current to a usable level requires an improvement of the rate of stimulated emission as well as the efficiency of the optical cavity.

Laser Diodes (heterostructure)

Methods for improvement:

1. ***Carrier confinement***. Confine the injected electrons and holes to a narrow region about the junction. This requires less current to establish the required concentration of electrons for population inversion.

2. Construct a dielectric waveguide around the optical gain region to increase the photon concentration and elevate the probability of stimulated emission. This reduces the number of electrons lost traveling off the cavity axis.

Summary: ***carrier confinement*** and ***photon confinement*** required

(a) A double heterostructure diode has two junctions which are between two different bandgap semiconductors (GaAs and AlGaAs).

(b) Simplified energy band diagram under a large forward bias. Lasing recombination takes place in the *p*-GaAs layer, the *active layer*

(c) Higher bandgap materials have a lower refractive index

(d) AlGaAs layers provide lateral optical confinement.

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Laser Diodes (double heterostructure)

Refer to the slide of the DH structure.

=>AlGaAs has Eg of 2 eV

$\Rightarrow$ GaAs has Eg of 1.4 eV

$\Rightarrow$ P-GaAs is a thin layer (0.1 – 0.2 um) and is the Active Layer where lasing recombination occurs.
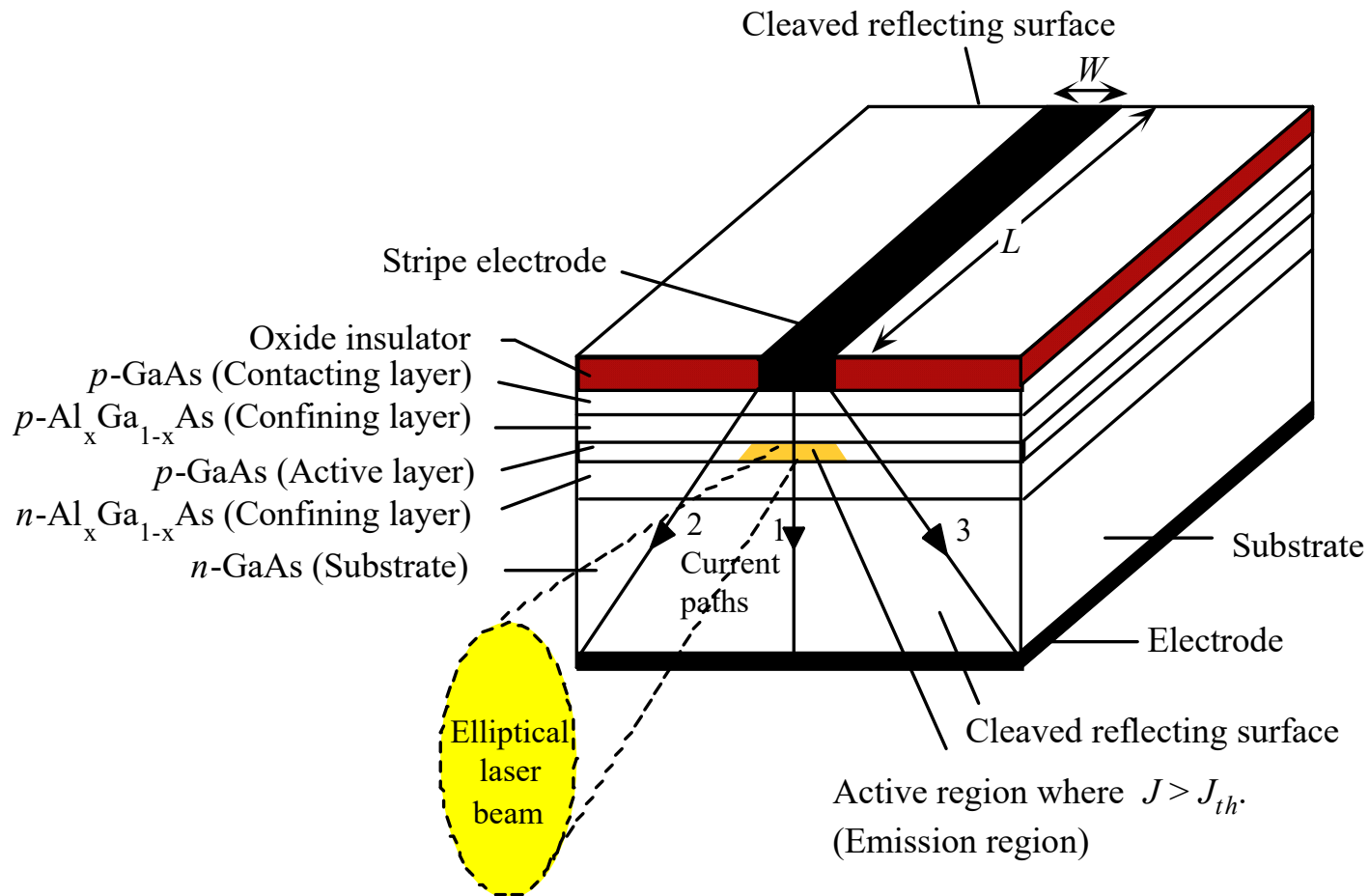
$\Rightarrow$ Both p regions are heavily doped and are degenereate with   in the VB.

E_F

$\Rightarrow$ With an adequate forward bias Ec of n-AlGaAs moves above Ec of p-GaAs which develops a large injection of electrons from the CB of n-AlGaAs to the CB of p-GaAs.

$\Rightarrow$ These electrons are confined to the CB of the p-GaAs due to the difference in barrier potential of the two materials.

Laser Diode (double heterostructure)

Note:1.Due to the thin p-GaAs layer a minimal amount of current only is required to increase the concentration of injected carriers at a fast rate. This is how threshold current is reduced for the purpose of poulation inversion and optical gain.

2. A semiconductor with a wider bandgap (AlGaAs) will also have a lower refractive index than GaAs. This difference in refractive index is what establishes an optical dielectric waveguide that ultimately confines photons to the active region.

Cleaved reflecting surface

W

L

Stripe electrode

Oxide insulator

p-GaAs (Contacting layer)

p-Al$_x$Ga$_{1-x}$As (Confining layer)

p-GaAs (Active layer)

n-Al$_x$Ga$_{1-x}$As (Confining layer)

n-GaAs (Substrate)

2 1 3

Current paths

Substrate

Electrode

Elliptical laser beam

Cleaved reflecting surface

Active region where $J > J_{th}$. (Emission region)

Schematic illustration of the the structure of a double heterojunction stripe contact laser diode

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Laser Diode (double heterostructure)

$\Rightarrow$ Substrate is n-GaAs

$\Rightarrow$ Confining layers are n-AlGaAs and p-AlGaAs

$\Rightarrow$ Active layer is p-GaAs (870-900nm)

$\Rightarrow$ Additional contacting layer is p-GaAs
(allows better electrode contact and avoids Schottky
junctions which limit current.

$\Rightarrow$ The p and n-AlGaAs layers provide carrier and optical
confinement by forming heterojunctions with the p-GaAs.

Laser Diodes(double heterostructure)

Advantage of AlGaAs/GaAs heterojunction is that they offer a small lattice mismatch between their crystal structures.

This introduces negligible strain induced interfacial defects (dislocations).

Defects of this nature act as non-radiative recombination centers.

Laser Diode (double heterostructure)

Stripe Geometry:

=>current density J is not uniform laterally from the stripe contact.

=>current is maximum along the central path and diminishes on either side with confinement between path 2 and 3. (gain guided)

=>population inversion and therefore optical gain occurs where current density exceeds threshold current values.

Adavantages of stripe geometry: 1. Reduced contact reduces threshold current. 2. Reduced emission area makes light coupling to fibre easier. (ex. Stripe widths of a few microns develop threshold currents of tens of milliamperes)

Laser Diode (fundamental characteristics)

What factors determine LD output spectrum?

1. The neature of the optical resonator that develops laser oscillations.

2. The optical gain curve (line-shape of active medium).

=>Optical resonator is a Fabry-Perot cavity.

=>length determines longitudinal modes where width and height of the cavity determines transverse or lateral modes.

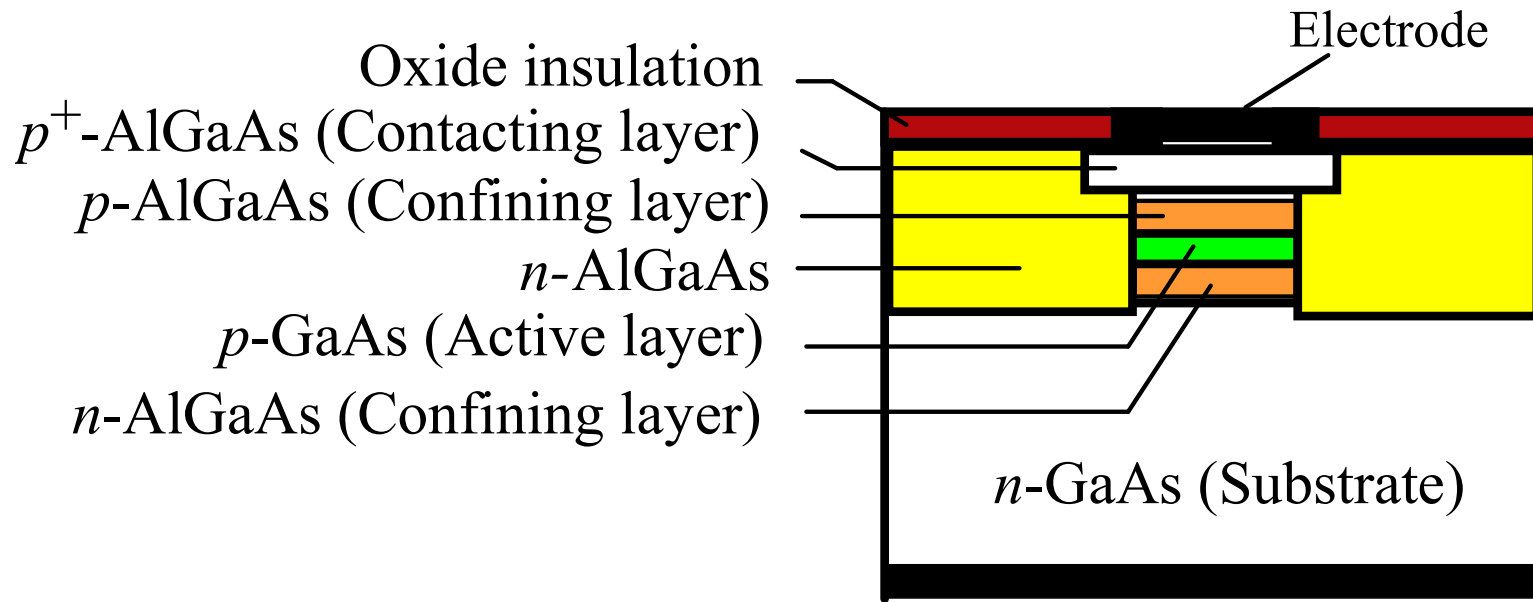=>with a sufficiently small W and H only the lowest transverse mode exits (TEM_{00}).

Laser Diode (fundamental characteristics)

   mode will have longitudinal modes whose separation depends on the length of the cavity.

=>Note: the exiting laser beam displays a diverging field due to diffraction at the ends of the cavity. The smaller the aperture the greater the diffraction.

=>The spectrum developed is either multimode or single mode determined by the geometry of the optical resonator and the pumping current level. Refer to slide of *index guided* LD.

Note the transition from multimode at low power to single mode at high power. Gain guided LDs tend to stay in multimode.

Oxide insulation

Electrode

p^+-AlGaAs (Contacting layer)

p-AlGaAs (Confining layer)

n-AlGaAs

p-GaAs (Active layer)

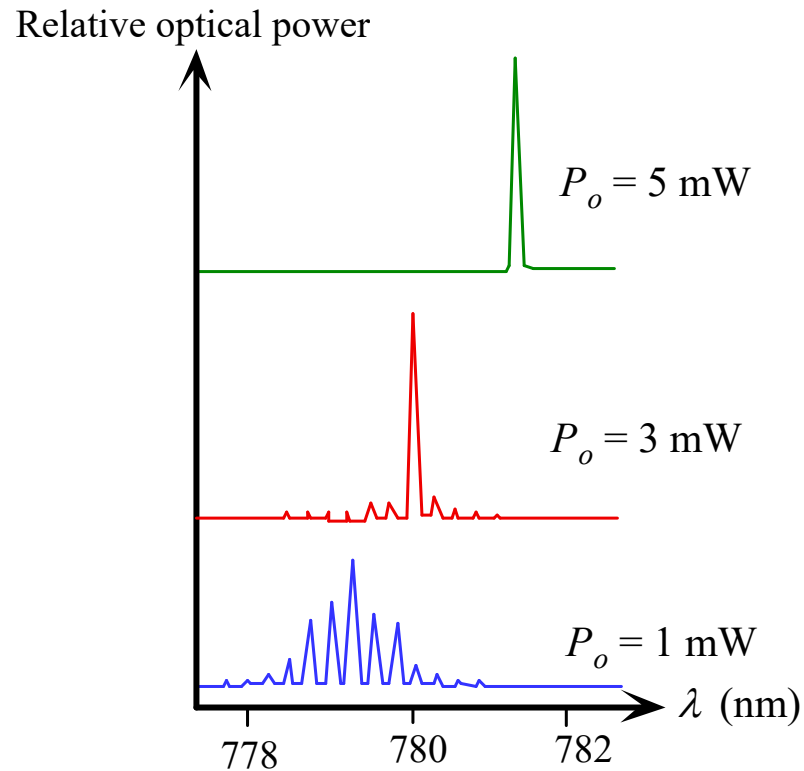n-AlGaAs (Confining layer)

n-GaAs (Substrate)

Schematic illustration of the cross sectional structure of a buried heterostructure laser diode.

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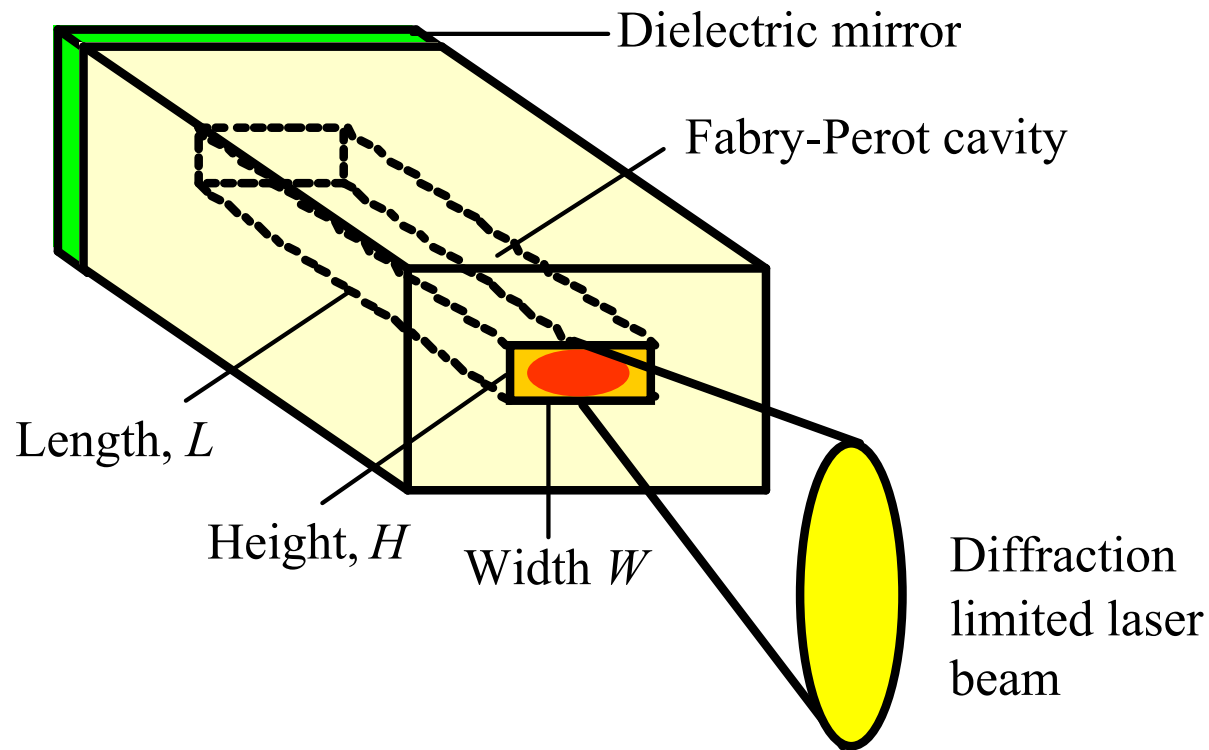
The laser cavity definitions and the output laser beam characteristics.

Output spectra of lasing emission from an index guided LD. At sufficiently high diode currents corresponding to high optical power, the operation becomes single mode. (Note: Relative power scale applies to each spectrum individually and not between spectra)

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Laser Diodes (temperature characteristics)

The output characteristics of an LD are sensitive to temperature.

=>As temperature increases threshold current increases exponentially.

$\Rightarrow$ Output spectrum also changes.

$\Rightarrow$ A single mode LD will mode hop (jump to a different mode) at certain temperatures.

$\Rightarrow$ This results in a change of laser oscillation wavelength.

$\Rightarrow$ λ_o increases slowly due to small change in refractive index and cavity length.
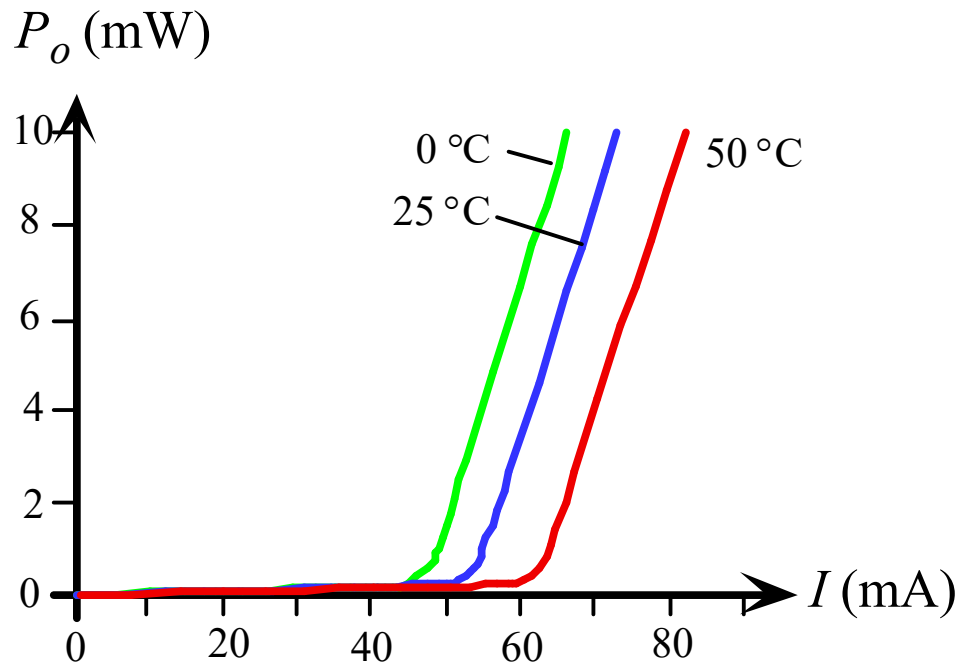
Output optical power vs. diode current as three different temperatures. The threshold current shifts to higher temperatures.
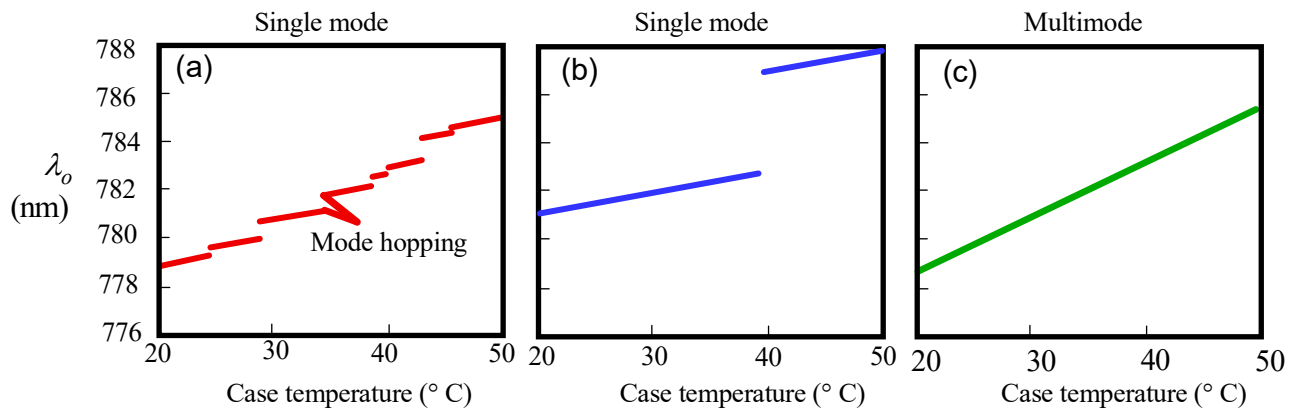
Laser Diodes (temperature characteristics)

Remedies if Mode Hop undesirable:

1.   Adjust device structure.

2.   Implement thermoelectric (TE) cooler.

Gain guided LDs inherently have many modes therefore the wavelength vs. temperature behaviour tends to follow the bandgap (optical gain curve as opposed to the cavity properties.

Peak wavelength vs. case temperature characteristics. (a) Mode hops in the output spectrum of a single mode LD. (b) Restricted mode hops and none over the temperature range of interest (20 - 40 °C). (c) Output spectrum from a multimode LD.
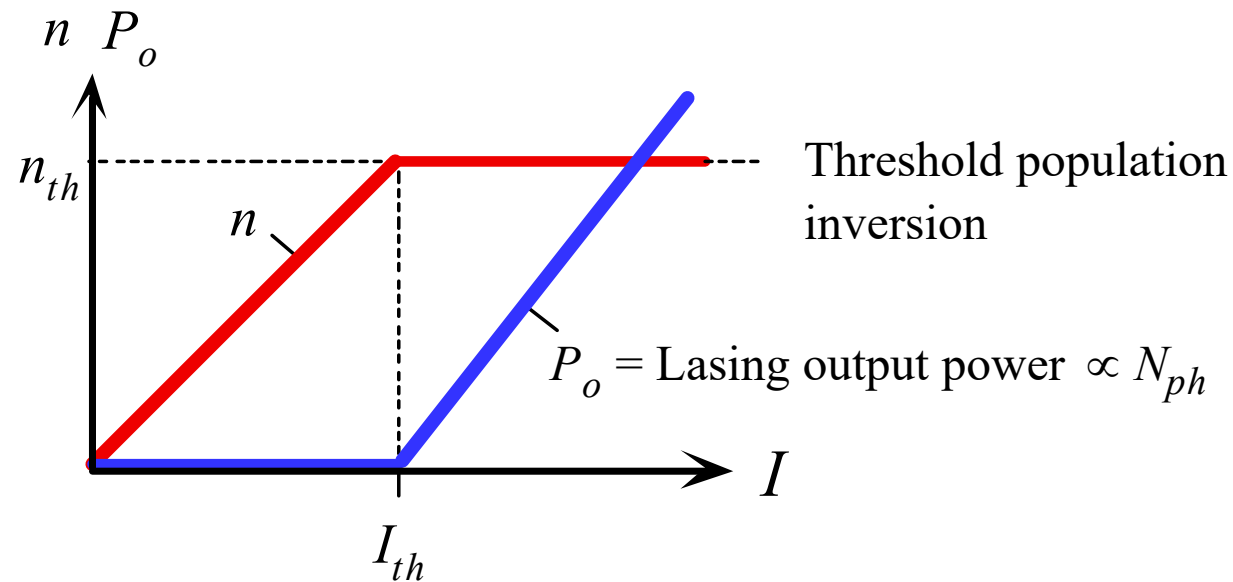
Laser Diodes (slope efficiency)

Slope efficiency determines the optical power (P_O) of the coherent output radiation related to diode current above I_{th} .
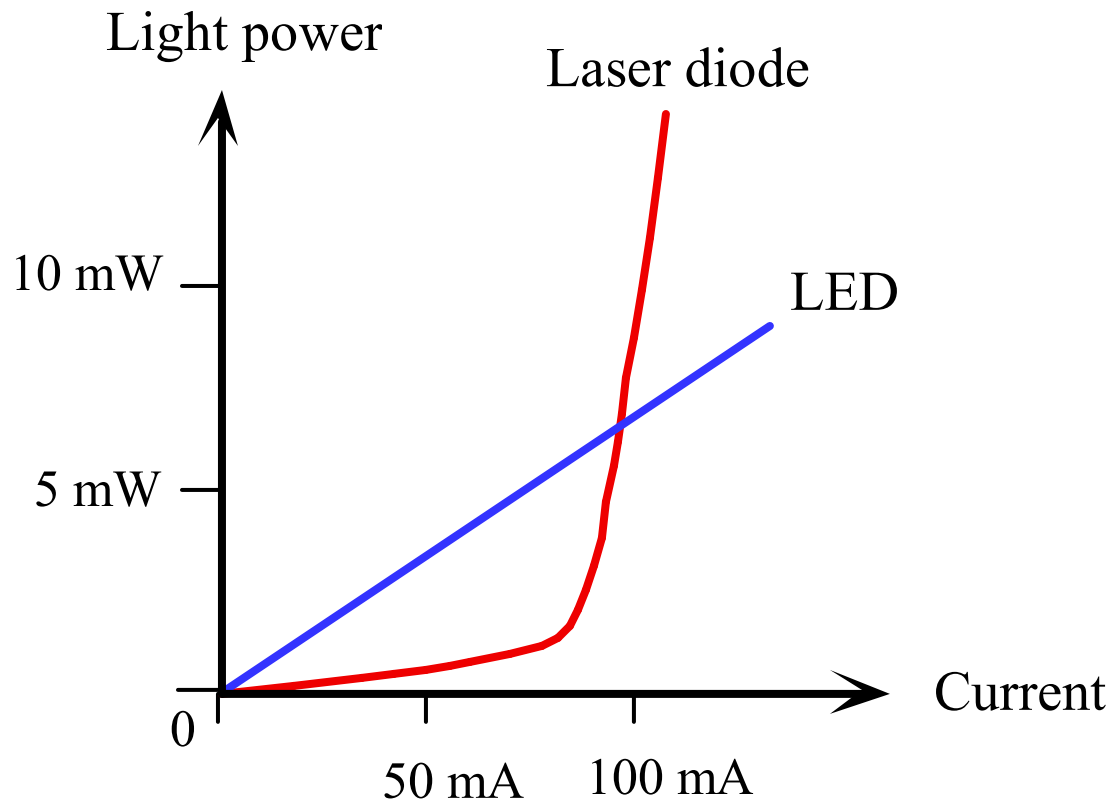
$$n_{slope} = \frac{P_O}{I - I_{th}}$$

$\Rightarrow$ W/A or W/mA

$\Rightarrow$ Slope efficiency dependant on device structure and semiconductor package.

$\Rightarrow$ Typically less than 1W/A

Simplified and idealized description of a semiconductor laser diode based on rate equations. Injected electron concentration n and coherent radiation output power P_o vs. diode current I.

Typical optical power output vs. forward current for a LED and a laser diode.