Lecture 21 - Laser Diodes - 2 - Outline

- **In-plane laser diodes, cont.** (continuing from Lect. 20)
  - Cavity design (in-plane geometries)
    - Vertical structure: homojunction, double heterojunction, quantum well, quantum cascade
    - Lateral definition: stripe contact, buried heterostructure, shallow rib
    - End-mirror design: cleaved facet, etched facet, DFB, DBR
  - Output beam shaping
- **Vertical cavity, surface emitting lasers (VCSELs)**
  - Basic concept, design and fabrication issues
  - Structures, technologies
- **In-plane surface emitting lasers**
  - Deflecting, etched mirrors
  - Second order gratings; holographic elements
- **Modulating laser diodes**
  - Small signal modulatioin
  - Step change response

Laser diodes: vertical design evolution

Double heterostructure:

The first major advance in laser diode design was the double heterostructure geometry which confines the carriers and the light to the same region.

The threshold current density is approximately

$$J_{th} = \frac{q\, n_{crit}\, d}{\tau_{\min}}$$

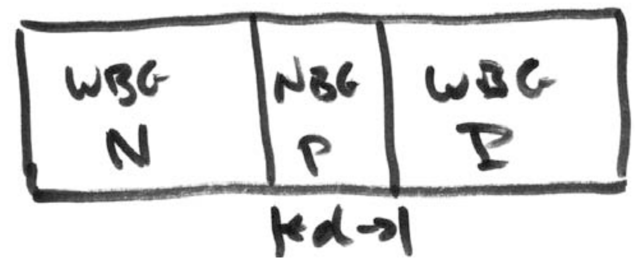
As predicted, and shown to the right, J_{th} decreases linearly with d until the guide layer is too thin to confine the light, at which point the overlap decreases and the threshold increases.

(Image deleted)

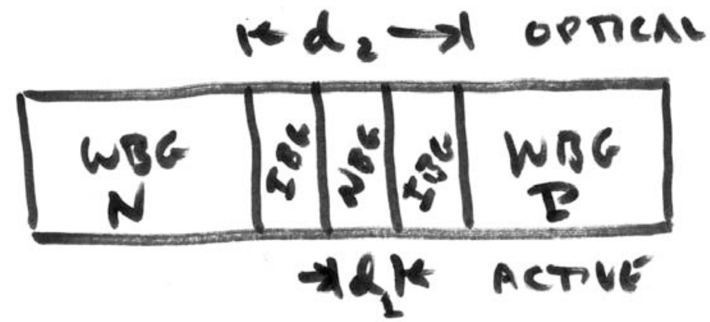
See Fig. 15-13(a) in: Yariv, A., Optical Electronics, New York: Holt, Rinehart and Winston, 1985.

Laser diodes: vertical design evolution

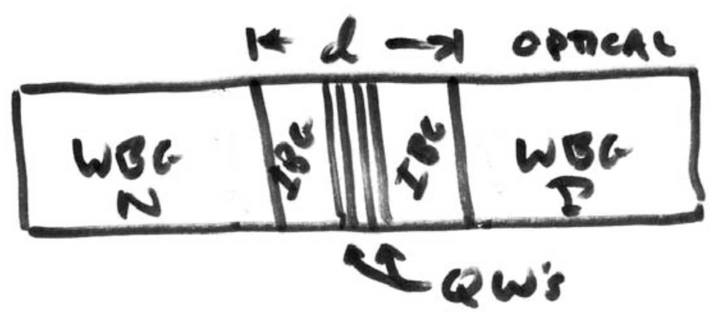
Double heterostructure:
carriers and light are confined by the same narrow bandgap layer. The threshold decreases with d until the optical mode spills out.



Separate confinement DH:
the waveguide and carrier confinement functions are done by different layers. The overlap is less, but the threshold is still reduced.

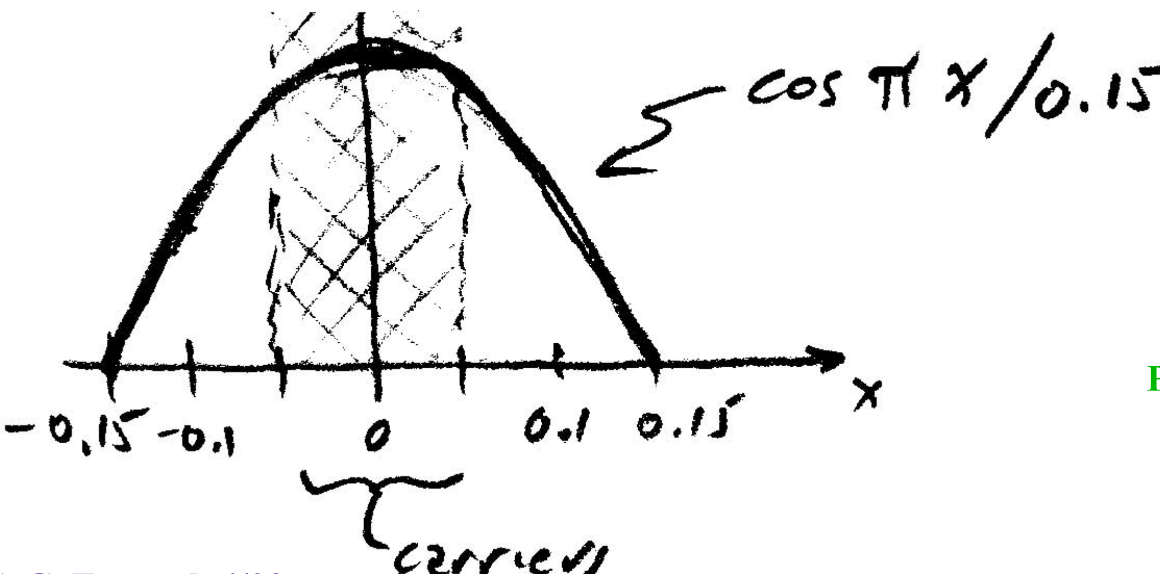


Quantum well: the overlap is less than in SCDH, but there is a net win because the quantum well transitions are stronger.



Laser diodes: Separate confinement issues

Overlap estimate: because the optical mode is peaked in the center of the waveguide the overlap of the mode and the inverted carrier population is greater than might first be expected. In the situation illustrated below, the inner layer is 1/3 the thickness, but the overlap overlap integral is only reduced by 1/2.



Waveguide portion options: the optical confinement/wave-guide layer is often graded by some means so the carriers can fall into the active or QW layers more easily:

Simple SCDH structure

Linearly grading

Parabolic grading

ep grading

Laser diodes: Further active layer evolution

Quantum wire and dot: Most of the work quantization beyond the quantum well has focused on quantum dots. An example applied to a VCSEL is shown to the right. The record low QD laser thresholds current densities are a few 10's of A/cm^2.

(Image deleted)

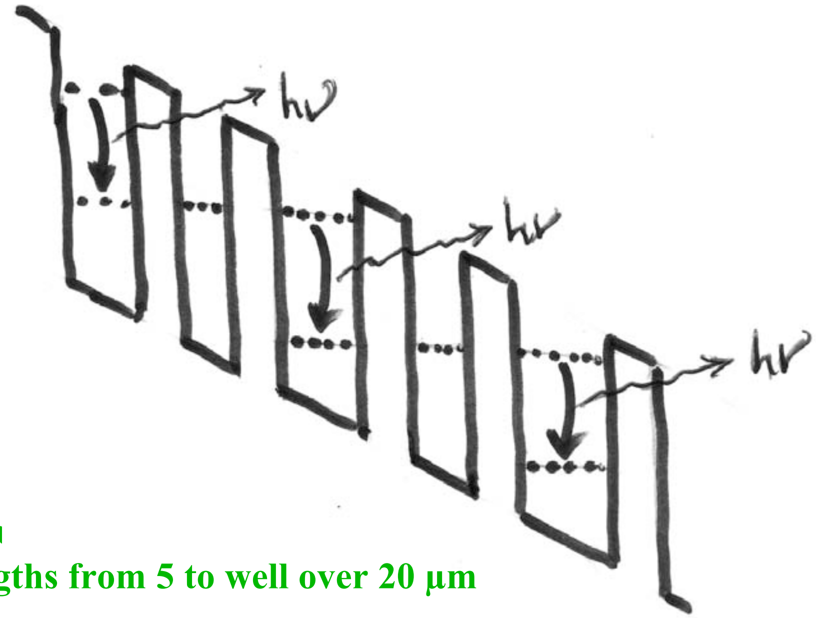
See Fig. 1 in S-F Tang et al, APL 78, No.17 (2001).

Strained quantum wells: As we saw earlier in the term, tensile and compressive strain modify the valence band energy levels and can enhance the transition strengths. Strained quantum wells are often used in laser diodes. The QWs are thin enough that the layers are pseudomorphic.

InGaAs QW (10% In) on GaAs
The well is in compression.

Laser diodes: Further active layer evolution

Quantum cascade lasers: To obtain lasing at long wavelengths people have historically relied on the use of very narrow bandgap lead-tin salts in traditional laser diode geometries. A more recent advance has been the use of the transitions between the levels in a quantum well.



Casca
lengths from 5 to well over 20 µm

(Image deleted)

See Fig. 1 in R. Colombelli et al, APL 78, No.18 (2001).

Many periods of an injector and active region multi-quantum well structure are used to obtain lasing of the n=2 to n=1 layer transition. In practice, complex superlattice structures like that shown to the left are used to optimize the performance.

Laser diodes: lateral design

Stripe contact geometries:

A laser diode with no lateral cavity definition is called a "broad area" diode.

A step of importance in increasing laser diode operating temperatures that was comparable to the introduction of the DH laser was the introduction of stripes to define the cavity laterally.

A wide variety of stripe structures have been used as the figures show.

Laser diodes: lateral design, cont.

Lateral optical confinement:

The stripes on the previous foils provide lateral current confinement (to varying degrees) but minimal optical guiding. To achieve optical guiding, more elaborate structures are used.

Laser diodes: horizontal design

Fabry-Perot cavity:

The traditional way of forming the primary laser cavity has been by cleaving the crystal to get parallel facets (see right), and using the reflection at the semiconductor-air interface.

Most modern in-plane lasers still use cleaved end-mirrors, often with coatings.

Mirrors can also be made by dry etching, but it is difficult to get them as vertical and parallel as is achieved by cleaving.

(Image deleted)

See Sze, S.M. Semiconductor Devices, Physics and Technology New York, Wiley, 1985.

<u>Laser diodes</u>: horizontal design, cont.

Fabry-Perot modes

(Image deleted)

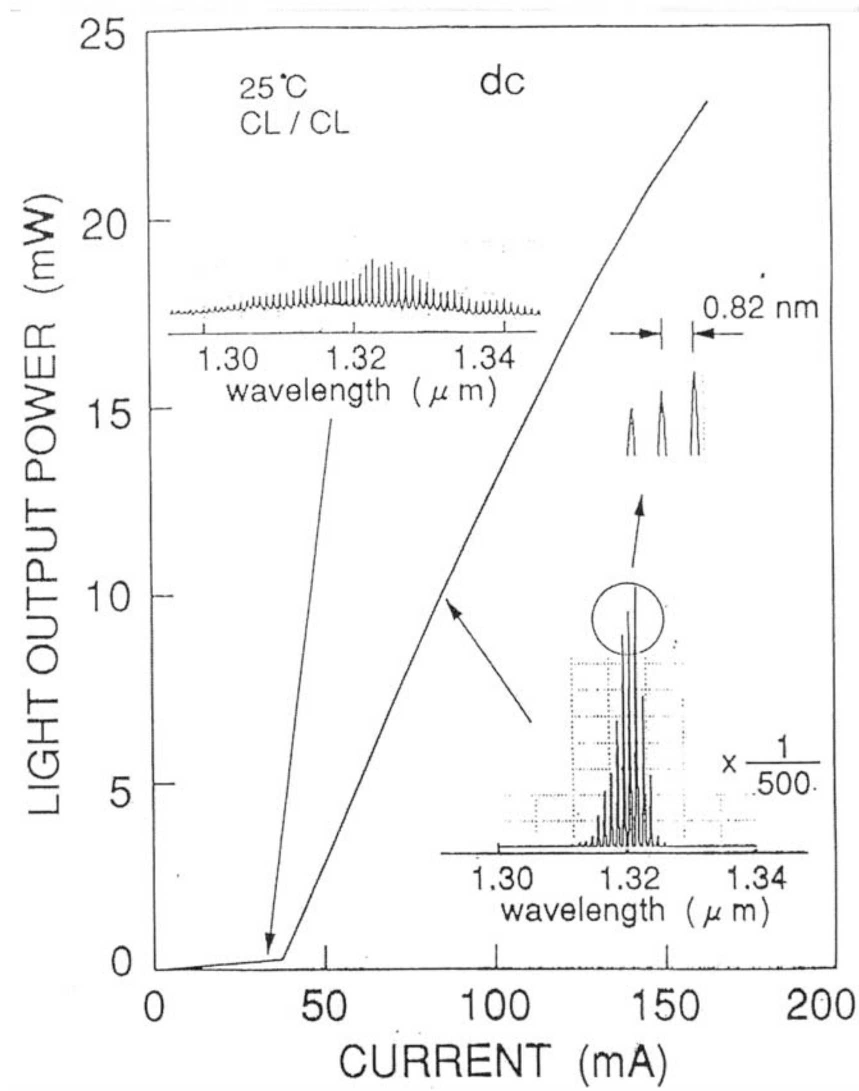
See Zappe, Hans P. *Introduction to Semiconductor Integrated Optics*, Fig. 9-12. pg. 240.

Laser diodes: horizontal design, cont.

Mode evolution above threshold:

It is interesting to note how the modes evolve in a cleaved-facet laser at currents near to, and well above threshold. Near threshold Fabry-Perot cavity modes appear on the output spectrum. As the current is raised well above threshold, one mode will ideally grow rapidly and dominate the spectrum.

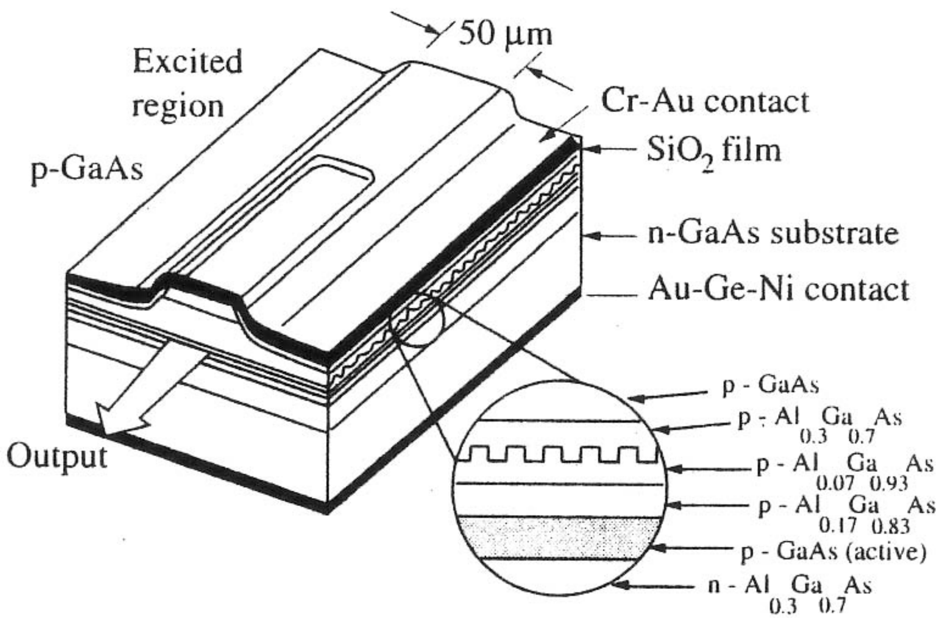
In the figure on the right there is not one dominate mode, which is not the desired situation.



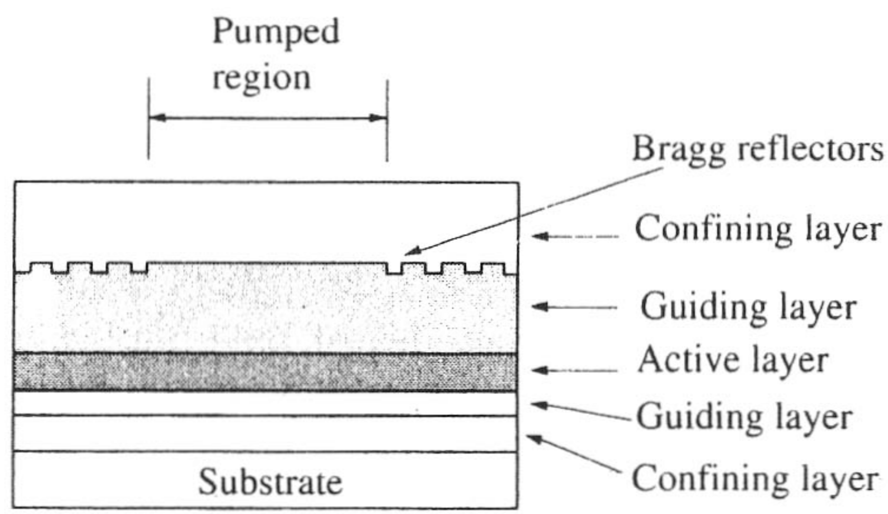
Laser diodes: horizontal design, cont.

Distributed Feedback:

Improved wavelength stability and control can be obtained using a distributed Bragg reflectors. By convention, when the distributed reflectors are within the active laser cavity the laser is called a DFB laser and when they are outside the active region on either end of the device the laser is called a DBR laser. Examples of each are shown below:



Distributed Feedback (DFB) Laser

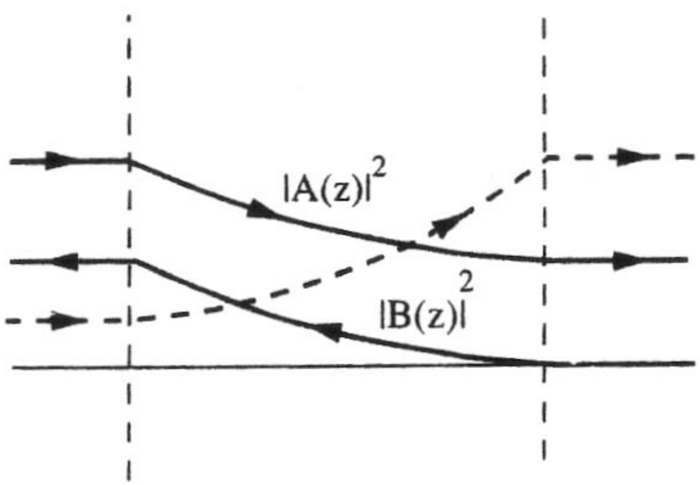


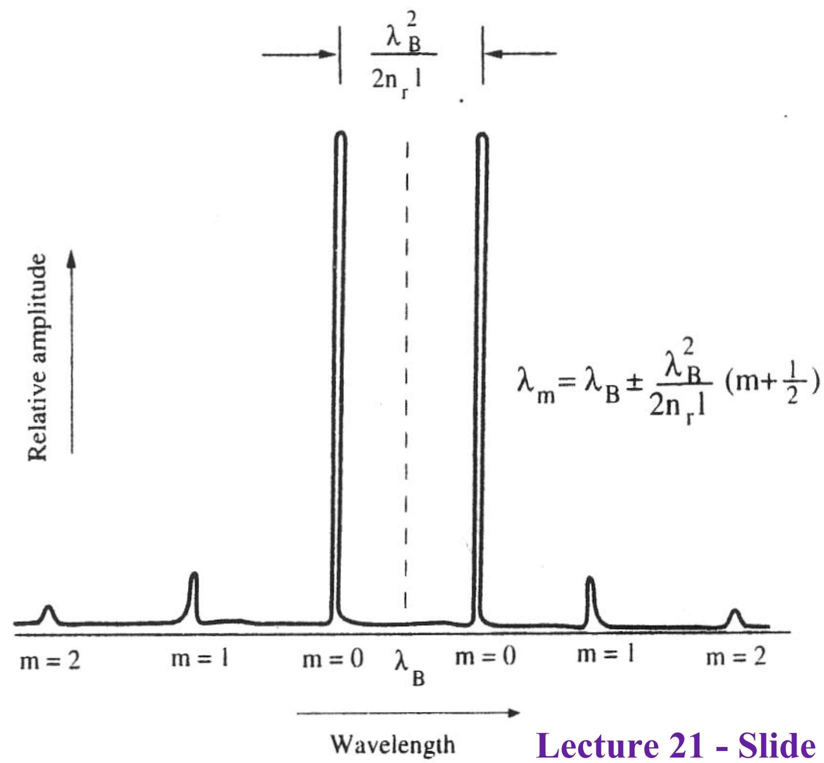
Distributed Bragg Reflector (DBR) Laser

Laser diodes: horizontal design, cont.

Distributed Feedback, cont:

The resonances of a DFB structure show the picket-fence Fabry-Perot structure, but the strength of the resonances are not the same as in a traditional FP cavity. Instead, the two modes on either side of the Bragg resonance are the strongest and thus are favored. This stabilizes the emission at one of these modes when the gain curve overlaps them. Adding a quarter wavelength shift between the two halves of the DFB structure can remove this degeneracy.





Forward and backward modes (above)

Spectral modes(right)

Laser diodes: surface emitting lasers

In-plane verses surface emitting **The attractions of surface emitting devices**

<u>Laser diodes</u>: surface emitting lasers

Etched deflector

Dry etching can be used to etch angled deflectors to achieve vertical emission.

Second order grating

A DBR laser with a second order grating (rather than first order) will have a mode normal to the surface

Vertical cavity surface emitting laser (VCSEL)

The dominant surface emitting laser is the VCSEL because it is relatively easier to make.

(Images deleted)

See Fig. 9.28 in Zappe, Hans P. *Introduction to Semiconductor Integrated Optics.*

Laser diodes: VCSELs, cont.

Device structures

a. Mesa; b. Ion implanted; c. Mesa with regrowth; d. Oxide confinement

Laser diodes: VCSELs, cont.

Oxidation of AlAs for current confinement

The conversion of AlAs to Al_2O_3 is widely used to confine the current to the center of a VCSEL

Oxidation rate of AlGaAs verses aluminum fraction

Oxidation rate of AlAs verses layer thickness