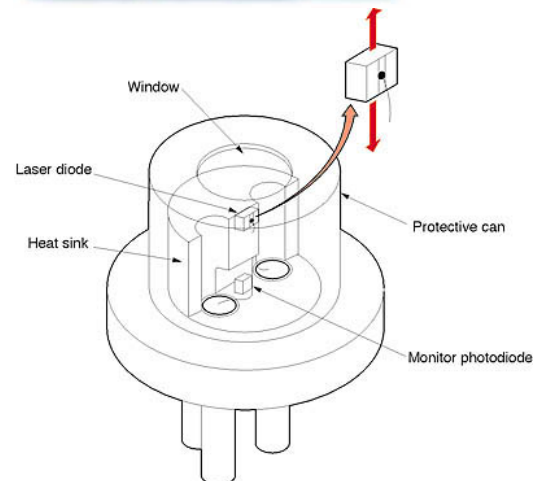
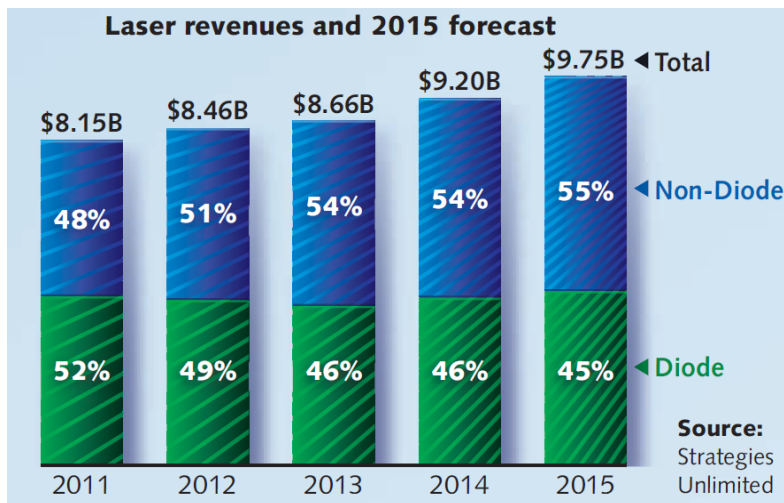
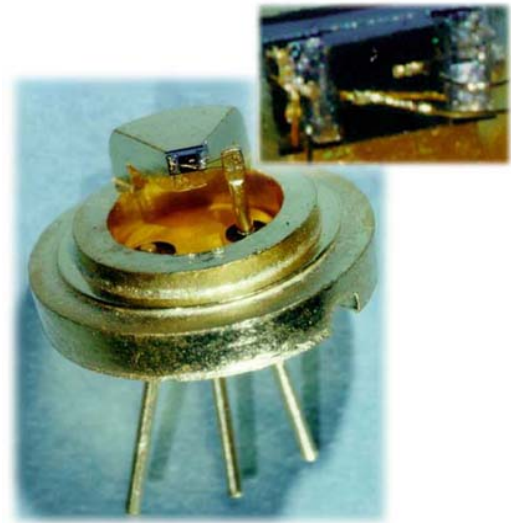
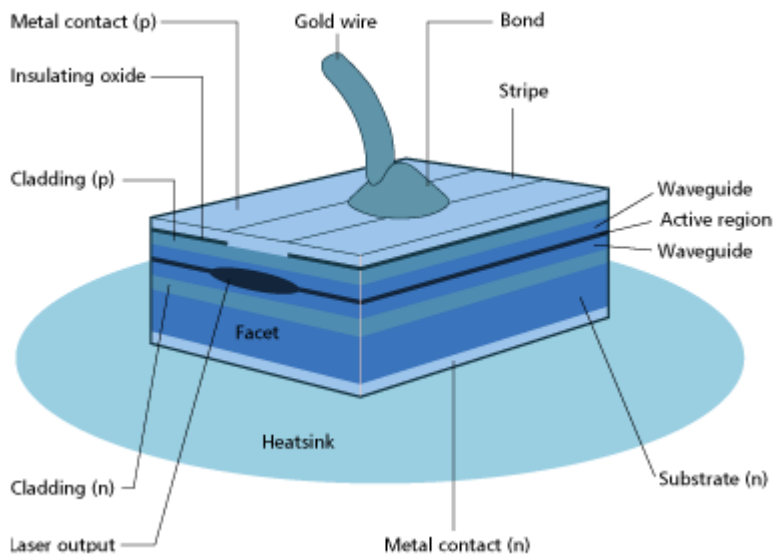


Semiconductor Lasers

- Semiconductors were originally pumped by lasers or e-beams
- First diode types developed in 1962:
- Create a pn junction in semiconductor material
- Pumped now with high current density
- Modified form of Light Emitting Diodes by creating cavity
- Ends of material “cleaved” into mirrors
- Currently the most common laser – 48% of market sales
- Driven by small size, high efficiency, low cost (<\$1)



Semiconductor Materials for Lasers

- Must use Direct Bandgap Materials:
eg III-V or II-VI compounds (refers to column in periodic table)
- Most common are GaAs, AlAs, InP, InAs combinations
- Si is an indirect bandgap material (except spongy Si)
- Indirect materials must emit an acoustic package
(phonon) during transition
- Very inefficient – thus Si cannot emit light in normal crystals
- Direct band: highly efficient emitters of light
- GaAs is a direct Bandgap
- Conversion efficiency $\sim 3x$ greater

| IIIA | | IVA | VA |
|----------------|-----------------|-----------------|----|
| 5 10.811 | 6 12.01115 | 7 14.0067 | |
| B Boron | C Carbon | N Nitrogen | |
| 13 26.9815 | 14 28.0855 | 15 30.9738 | |
| Al Aluminum | Si Silicon | P Phosphorus | |
| 31 69.72 | 32 72.34 | 33 74.922 | |
| Ga Gallium | Ge Germanium | As Arsenic | |
| 49 114.82 | 50 118.69 | 51 121.75 | |
| In Indium | Sn Tin | Sb Antimony | |
| 81 204.37 | 82 207.19 | 83 208.980 | |
| Tl Thallium | Pb Lead | Bi Bismuth | |

Elemental Semiconductors

III - V Compound Semiconductors

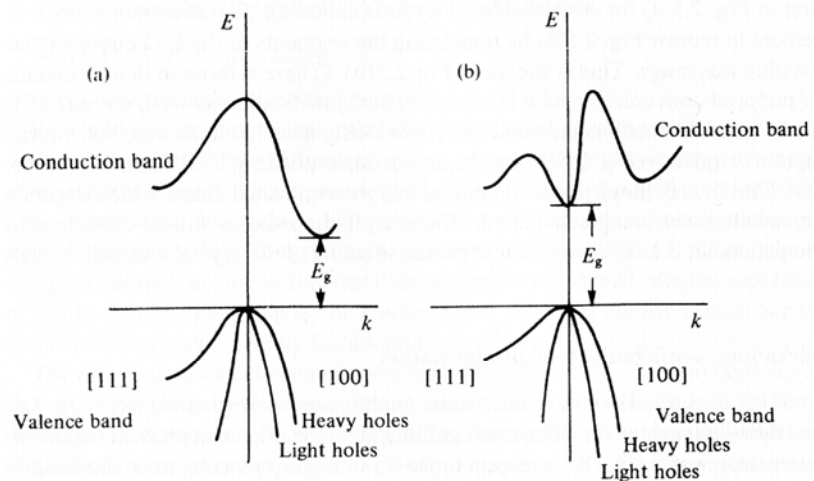


FIG. 2.6 Relationship of $E-k$ for real solids: (a) silicon (which has an indirect bandgap) and (b) gallium arsenide (which has a direct bandgap). The figure shows the conduction and valence bands and the energy gap E_g between them. Note that (i) k is specified in different crystallographic directions to the left and right and (ii) there are holes present with different effective masses (sections 2.2.1 and 2.3).

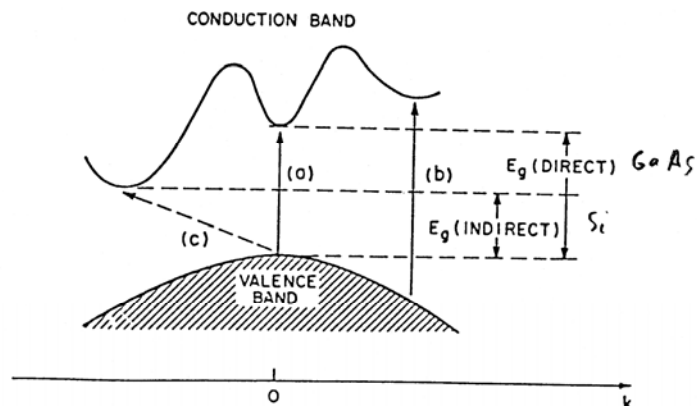


Fig. 2.6 Optical transitions: (a) and (b) direct transitions; (c) indirect transition involving phonons.

Lasers and Light Emitting Diodes

- Operates like PN junction diode
- Abrupt junction of P doped and N doped regions
- Homojunction: materials the same
- Hetrojunction: P and N materials different
- Need direct bandgap materials
- When reversed biased no light
- When forward biased by high current
- Conduction electrons directly over valance holes
- Hole falls into electron: creates light

$$E = h\nu \quad \text{and} \quad \lambda = \frac{hc}{E_g}$$

$$h = 4.13 \times 10^{-15} \text{ eV}$$

$$hc = 1.24 \text{ } \mu\text{m eV}$$

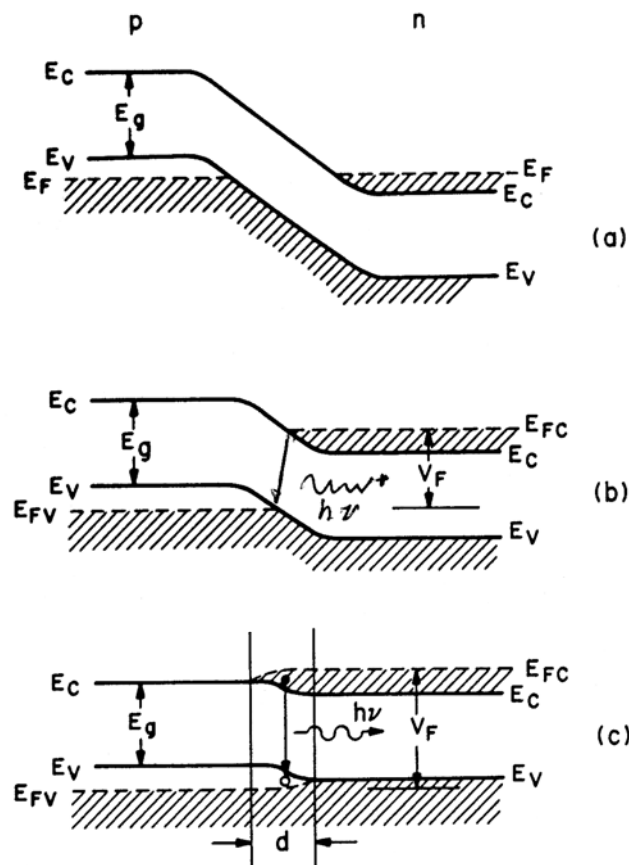


Fig. 19 Energy band diagrams of a degenerate p - n junction (a) at thermal equilibrium, (b) under forward bias, and (c) under high-injection condition.

Materials And LED's

- Different Colours of LED's require different bandgaps
- Most important are combinations of III-V's or II-VI's
- Especially GaAs-GaP combinations
- Current behaviour of LED is

$$I_D = I_{nonradiative} + I_{radiative}$$

$$I_D = I_s \left[\exp\left(\frac{V_D q}{KT}\right) - 1 \right] + I_{RG} \left[\exp\left(\frac{V_D q}{2KT}\right) - 1 \right]$$

where I_s = reverse saturation current

I_{RG} = Recombination/Generation current

- To maximize current must get
- low currents dominated by nonradiative recombination
- Medium by radiative diffusion current
- High by contact resistances

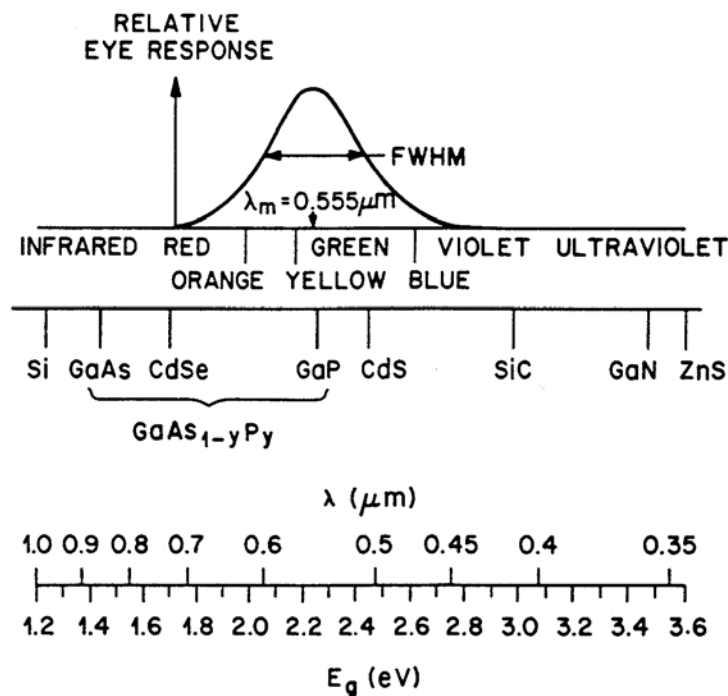
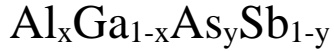
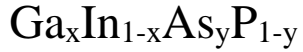


Fig. 6 Semiconductors of interest as visible LEDs. Figure includes relative response of the human eye.

Quaternary and Pentenary Alloy systems

- Can mix both III and V compounds or higher
- Gives much more freedom in Bandgap & Lattice
- Common Examples



- Extreme example uses I-III-VI compounds



TABLE 18.1 Some Semiconductor Laser Materials

| Compound | Wavelength, nm | Notes |
|--|----------------|---|
| AlGaInP | 630–680 | Shortest wavelengths are recent developments; higher power at longer wavelengths. |
| Ga _{0.5} In _{0.5} P | 670 | Active layer between AlGaInP layers; long room-temperature lifetime |
| Ga _{1-x} Al _x As | 620–895 | $x = 0-0.45$; lifetimes very short for wavelengths < 720 nm |
| GaAs | 904 | Strained-layer superlattice, on GaAs substrate |
| In _{0.2} Ga _{0.8} As | 980 | |
| In _{1-x} Ga _x As _y P _{1-y} | 1100–1650 | InP substrate |
| In _{0.73} Ga _{0.27} As _{0.58} P _{0.42} | 1310 | Major fiber communication wavelength |
| In _{0.58} Ga _{0.42} As _{0.9} P _{0.1} | 1550 | Major fiber communication wavelength |
| InGaAsSb | 1700–4400 | Possible range, developmental, on GaSb substrate |
| PbEuSeTe | 3300–5800 | Cryogenic |
| PbSSe | 4200–8000 | Cryogenic |
| PbSnTe | 6300–29,000 | Cryogenic |
| PbSnSe | 8000–29,000 | Cryogenic |

Mixed Alloys

- Gives a wide range of wavelengths available
- Can get visible to far infrared

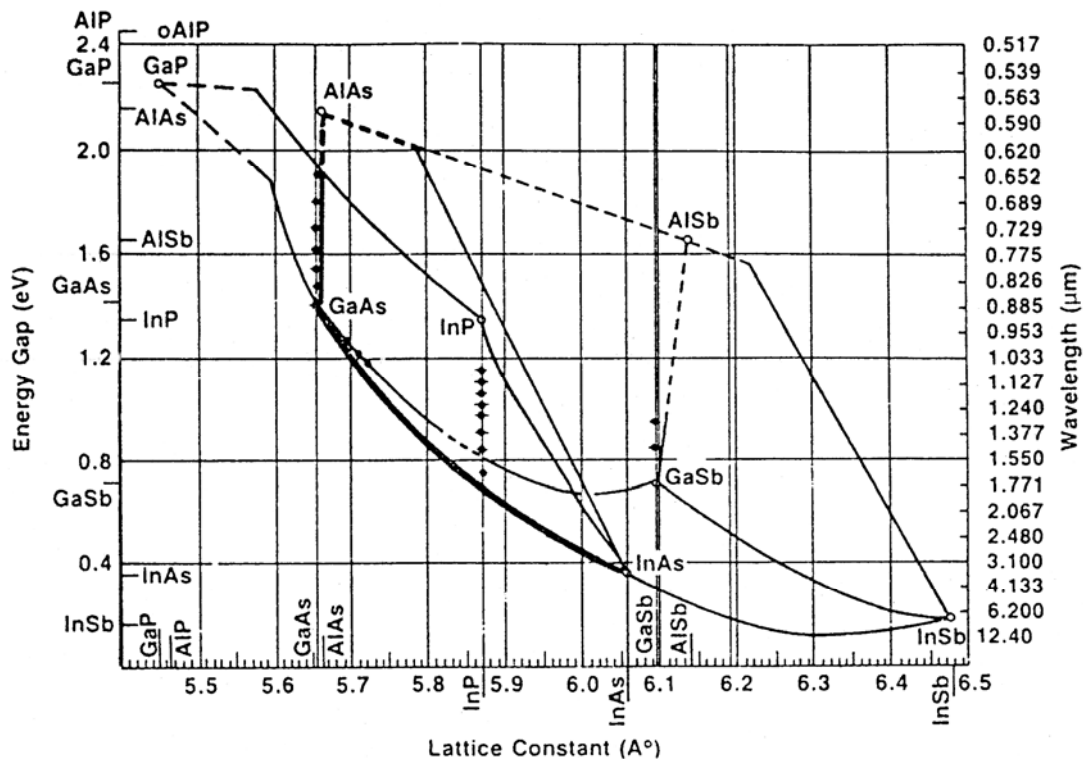
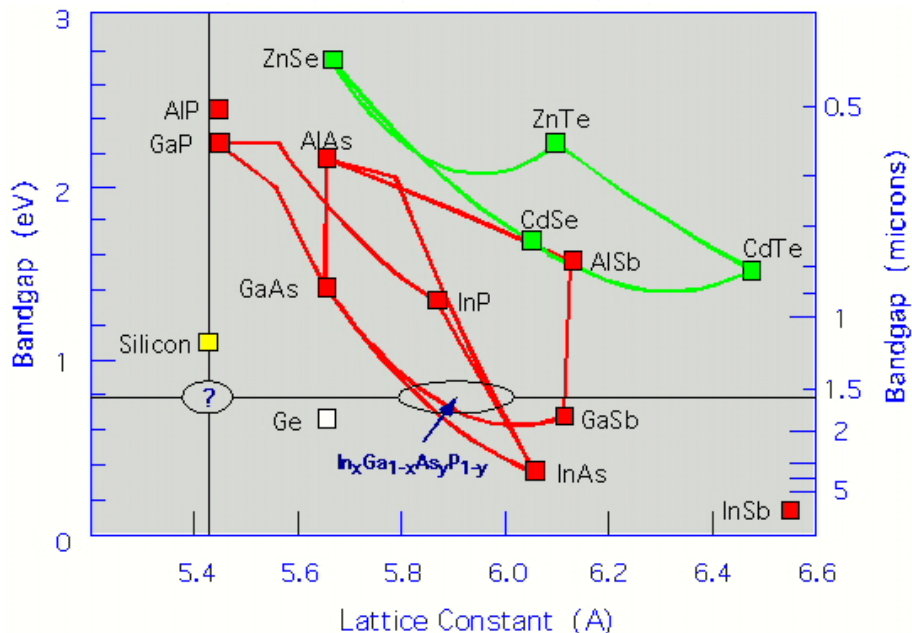


Figure 19.3 Energy bandgap and lattice constants for III to V bulk semiconductors. Dashed lines indicate indirect-bandgap materials not suitable for laser operation; solid lines are direct-bandgap materials. Lines that connect points for binary compounds represent values of intermediate ternary compounds; for example, GaAlAs characteristics fall along the line connecting GaAs with AlAs. Possible characteristics of quaternary compounds fall inside the area defined by the four possible binary compounds (e.g., GaAs, GaP, InAs, and InP for InGaAsP). Bulk lasers must be lattice-matched to a substrate. [Courtesy of P. K. Tien. From Kapon (1989), with permission]



Materials Development Key to LED's

- Key to making any LED/Laser diode is growing the material
- Must grow good crystals on the right substrate
- Material must not be damaged by the high current
- First LED, Biard and Pittman GaAs in 1961, IR at 900 nm
- Red LED by Holonyak, Jr. in 1962 using GaAsP
- Yellow LED by Craford increased efficiency by 10X
- Green LEDs were weak but by 2000's became strong AlGaInP
- Blue LED's were first done in 1972 with GaN but very weak
- 1992 Nakamura created InGaN high power Blue LED's
- Akasaki, Amano developed low cost InGaN/GaN structures
- 2014 Nobel Physics prize to Nakamura, Akasaki, Amano
- Blue LED are coated with a phosphor: Cesium doped YAG
- Shifts the Blue light to yellow creating White LED's
- Super Bright LEDs now target for replace fluorescent lights



Optical Light Confinement

- When first tried could only lase when cooled below 77°K
- Key to operation: LED's and Laser Diodes use light confinement
- When have high index surrounding low index
get beam confined by Total Internal Reflection
- Called Optical confinement or Waveguide
- Recall Total Internal Reflection formula

$$\sin(\phi_c) = \frac{n'}{n}$$

- Use thin layers of different materials or different doping level
- both change index of refraction

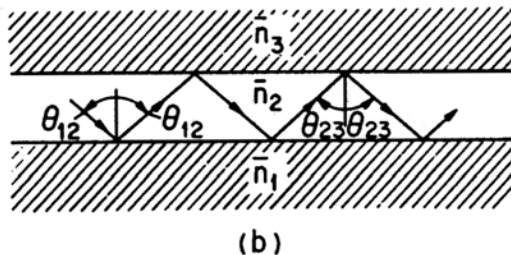
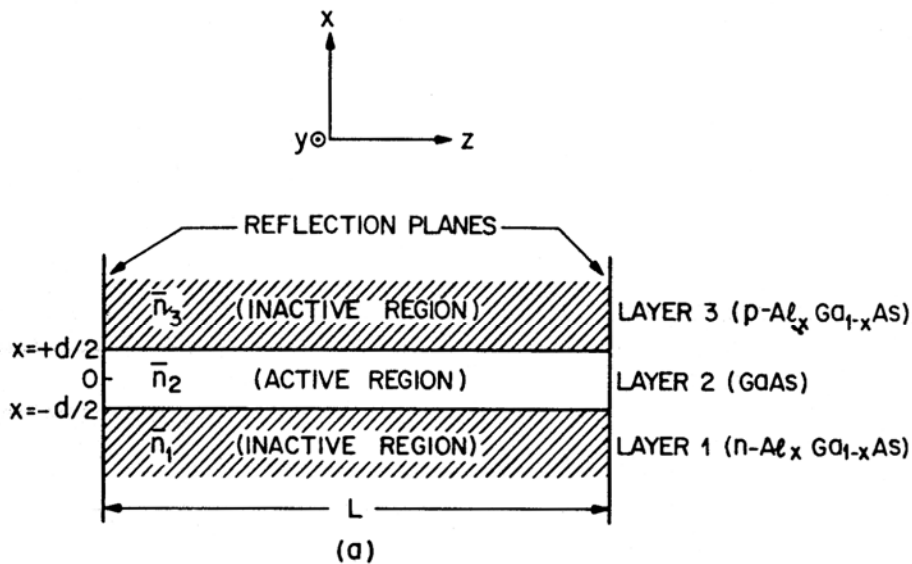


Fig. 29 (a) Representation of a three-layer dielectric waveguide. (b) Ray trajectories of the guided wave.

Light Emitting Diode Structure

- LED's Consist of GaAsP mixed alloy structures
- Different materials: different index of refraction
- Use either back absorption or back reflection

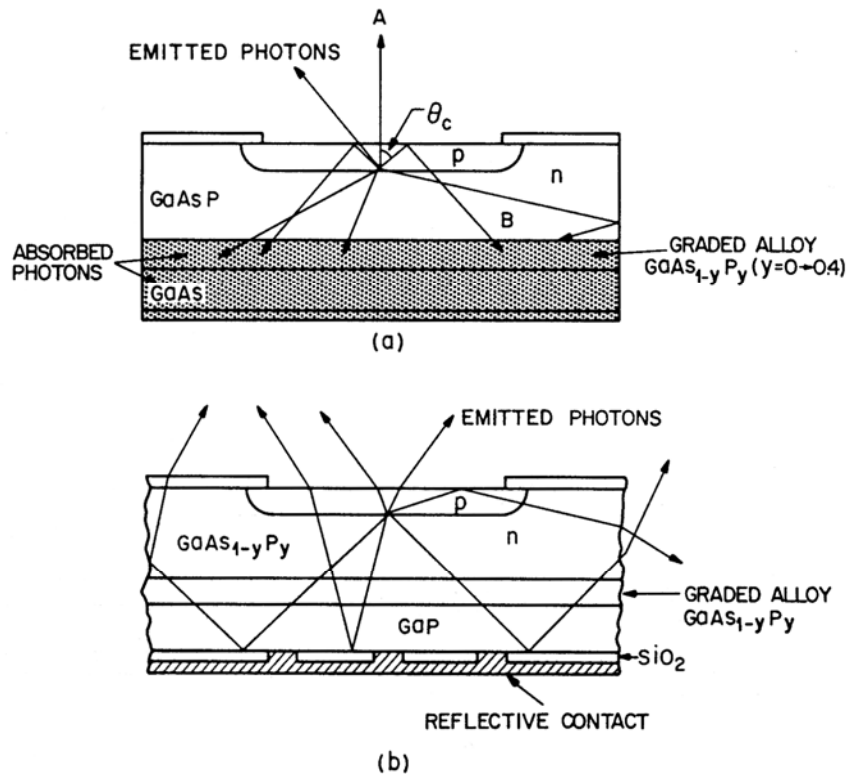
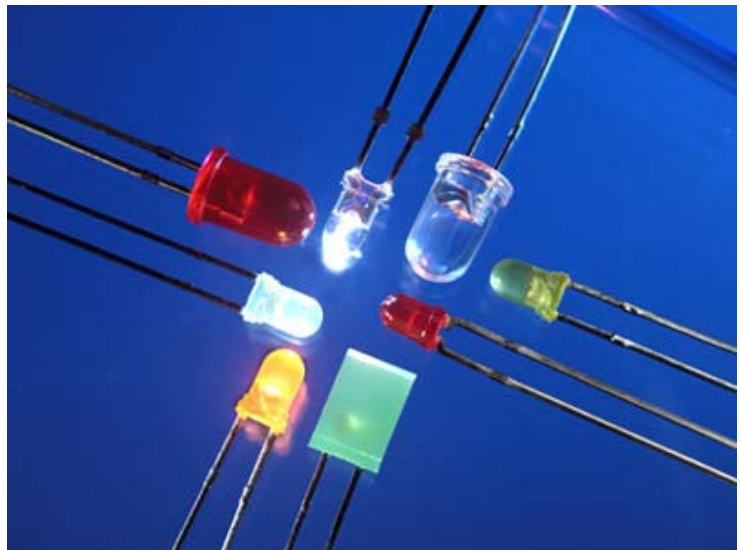
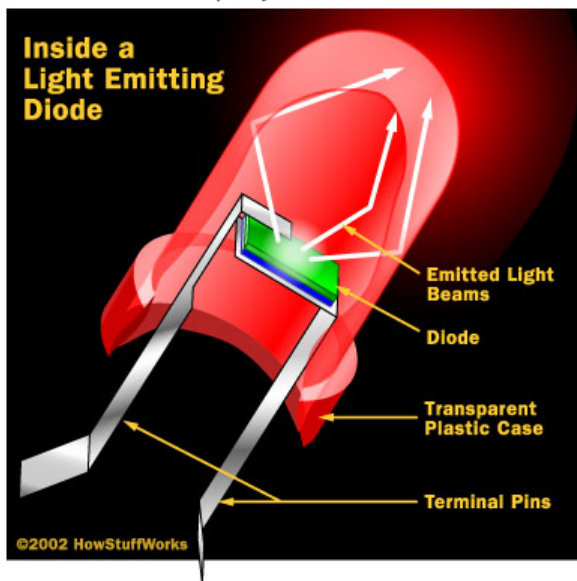


Fig. 9 Effects of (a) opaque substrate and (b) transparent substrate on photon emitted at the p - n junction.⁶



PN Junction Diode Laser

- At low pumping get LED
- With right cavity shape get laser

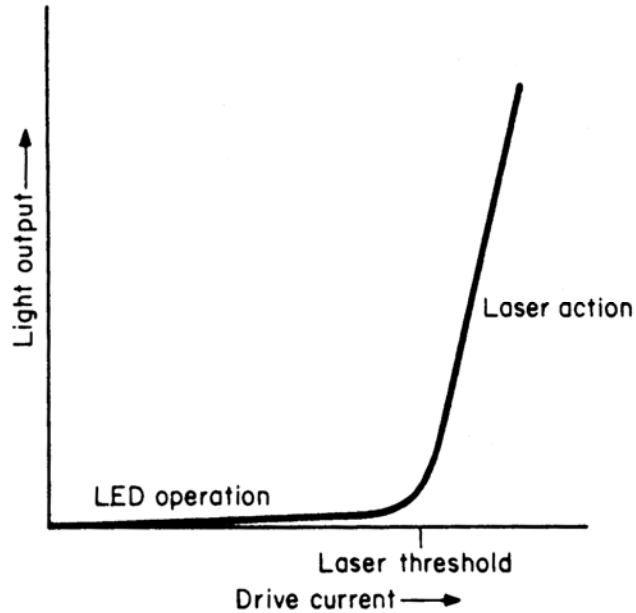


Figure 18.3 Output of a laser diode below threshold (when it operates as an LED) and above threshold (when it operates as a laser). The much steeper slope for laser operation indicates higher-efficiency emission.

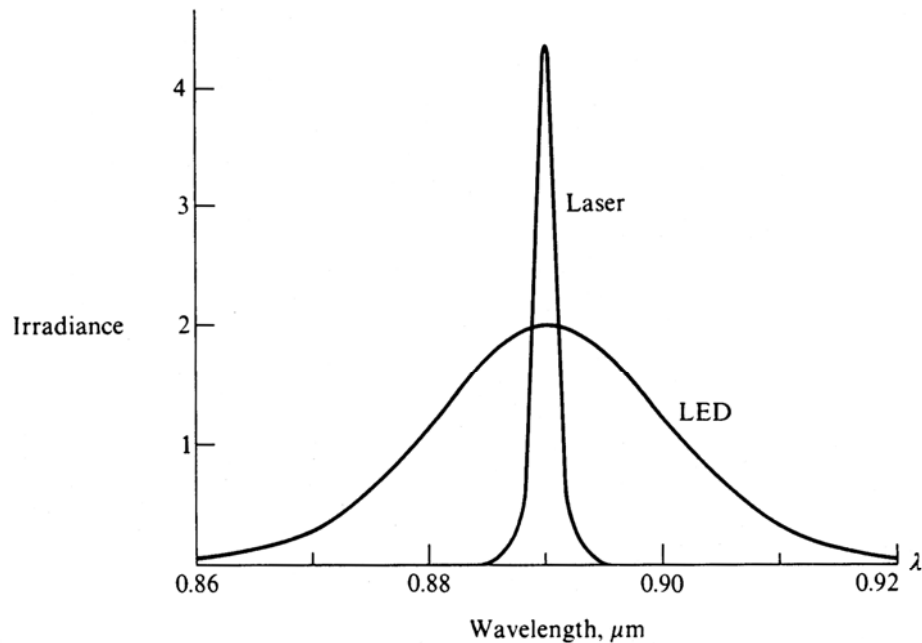


Fig. 6.25 Emission spectrum of a semiconductor laser compared to that of an LED operating below threshold.

Simple Homojunction Diode Laser

- Homojunction: materials the same on both sides of the Junction
- Some confinement: small index of refraction difference for n & p
- Abrupt junction of P doped and N doped regions
- Emission confined to junction area
- Mirrors created by cleaving rods
- Uses crystal planes to create smooth mirrors (change in n mirrors)
- Highly Elliptical emission: 1×50 microns
- Problem: light not vertically confined = $30^\circ \times < 1^\circ$ beam
Hence requires very high threshold current & device cooling
Often only operates as laser at Liquid Nitrogen temp (77°K)
- Homojunction where first type of laser diodes
- Hetrojunction better: P and N materials different

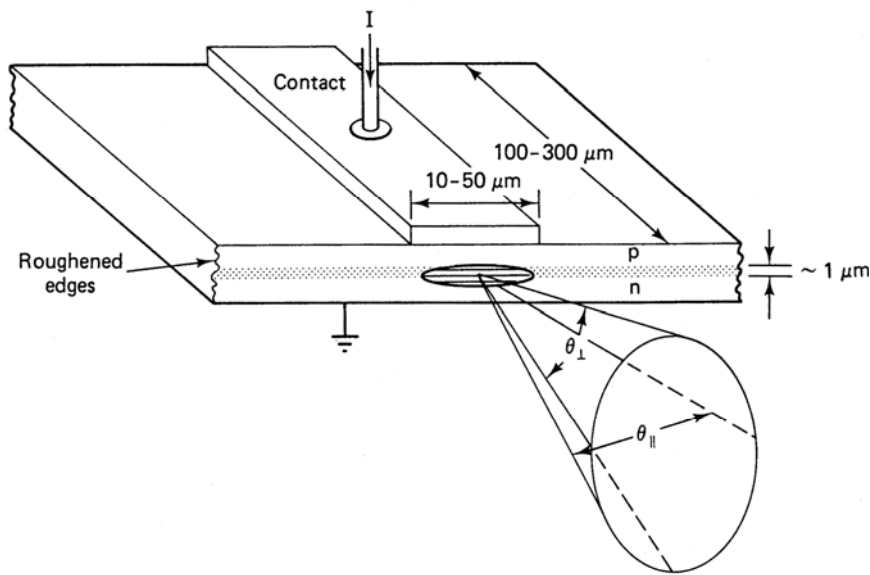
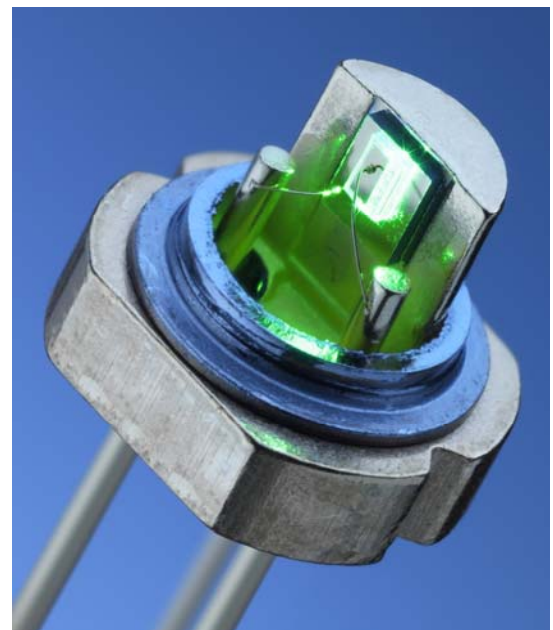


Figure 11.11 The radiation field of a semiconductor laser.



Heterojunctions Laser

- Heterojunction diode: different materials for n & p
- Different materials: significantly different index n
- Also different lattice constants
- Important point: want the lattice matched at layer boundary
- Use mixed alloy: eg GaAs and AlAs



- x = mole fraction of Aluminum
- 1-x = mole fraction of Gallium

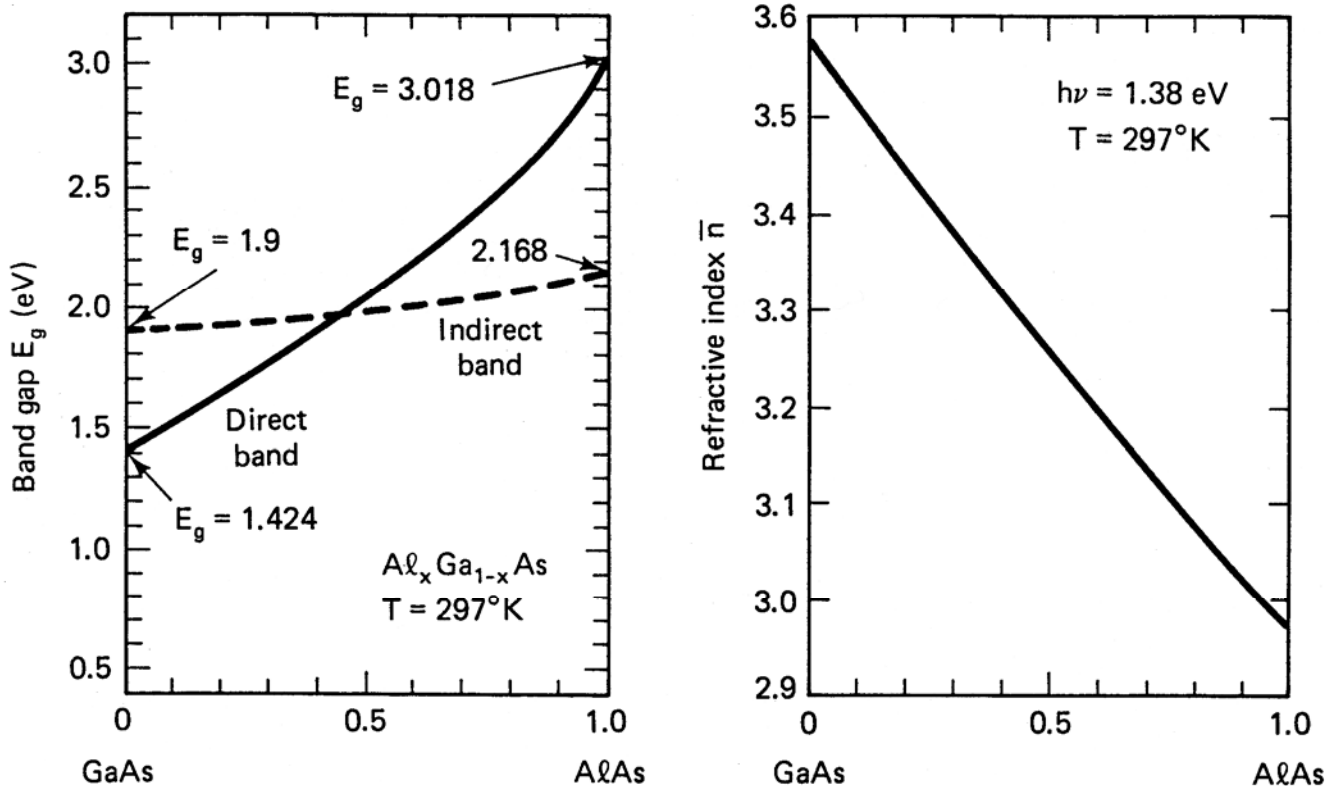


Figure 11.12 Mole fraction AlAs, x. Dependence of the band gap and index of refraction of $\text{Al}_x\text{Ga}_{1-x}\text{As}$ on the amount of aluminum. (Data from Casey and Panish.²²)

Heterojunctions Laser

- Single Heterojunctions: one sided confinement
- p-GaAlAs: p-GaAs: n-GaAs
- Better confinement means lower threshold current for lasing
- Thus operates in pulsed mode at room temperature
- Double Heterojunction lasers: confines both top & bottom
- p-GaAlAs: GaAs: n-GaAlAs: n-GaAs

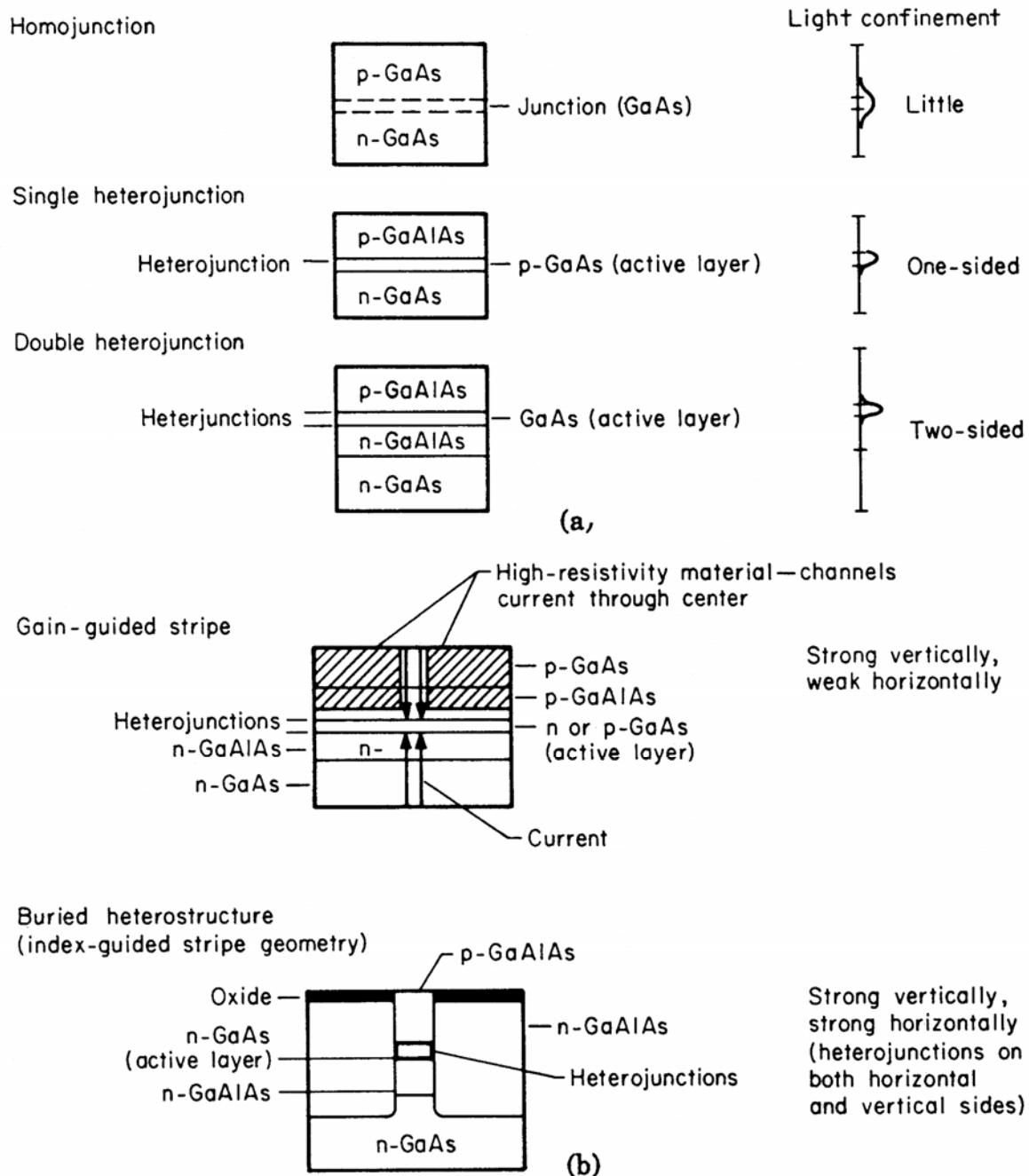


Figure 18.5 Major categories of edge-emitting diode lasers. (a) Three types shown in side views; (b) end views.

Double Heterojunctions Laser

- Has both Band and Index steps on both top & bottom
- Doubly confines light: creates a waveguide as cavity
- Requires much less threshold current
- Thus CW operation now possible at room temperature

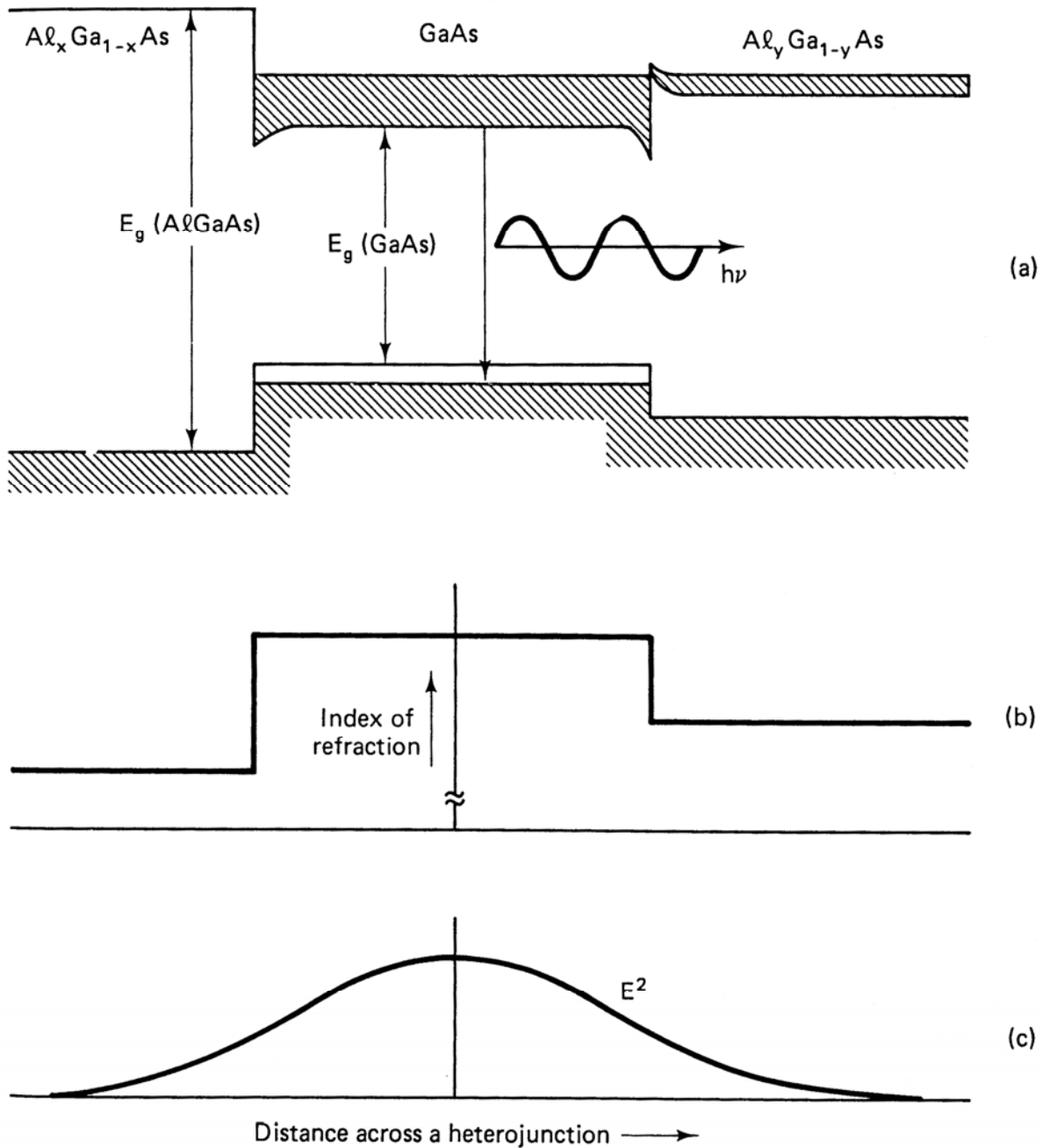


Figure 11.13 The band diagram for a forward-biased heterostructure in (a), the refractive index in (b), and a sketch of the light intensity in the vicinity of the active region in (c).

Comparison of Homo/Hetero/D-Heterojunctions Lasers

- As add index steps get smaller light spreading
- Single heterojunction threshold current $\sim 5\times <$ homojunction
- Double heterojunction threshold $\sim 50\text{-}100\times <$ homojunction
- Less current, less heating, more output before thermal limitations

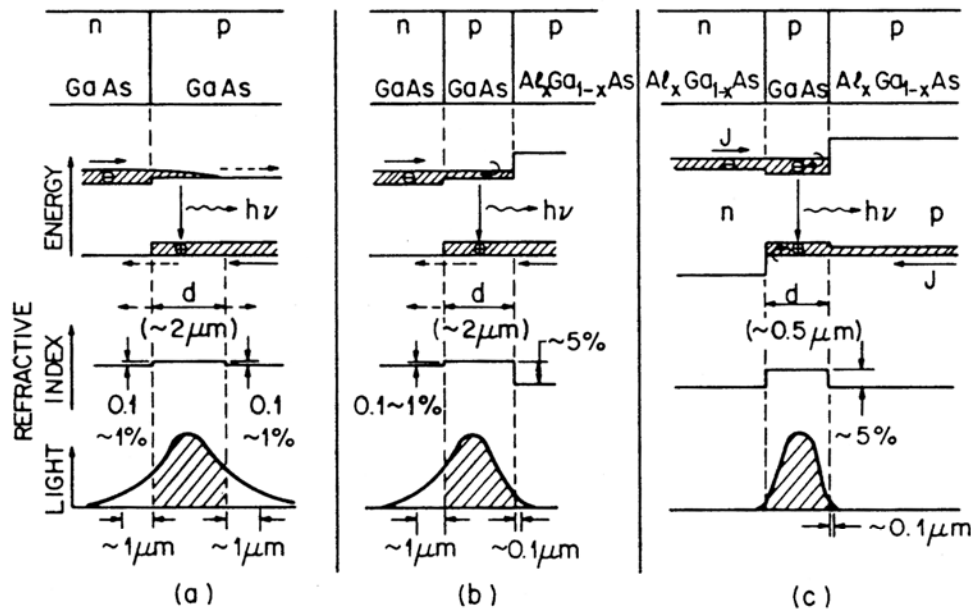


Fig. 27 Comparison of some characteristics of (a) homostructure, (b) single-heterostructure, and (c) double-heterostructure lasers. The top row shows energy-band diagrams under forward bias. The refractive index change for GaAs/ $\text{Al}_x\text{Ga}_{1-x}\text{As}$ is about 5%. The change across a homostructure is less than 1%. The confinement of light is shown in the bottom row. (After Panish, Hayashi, and Sumski, Ref. 48.)

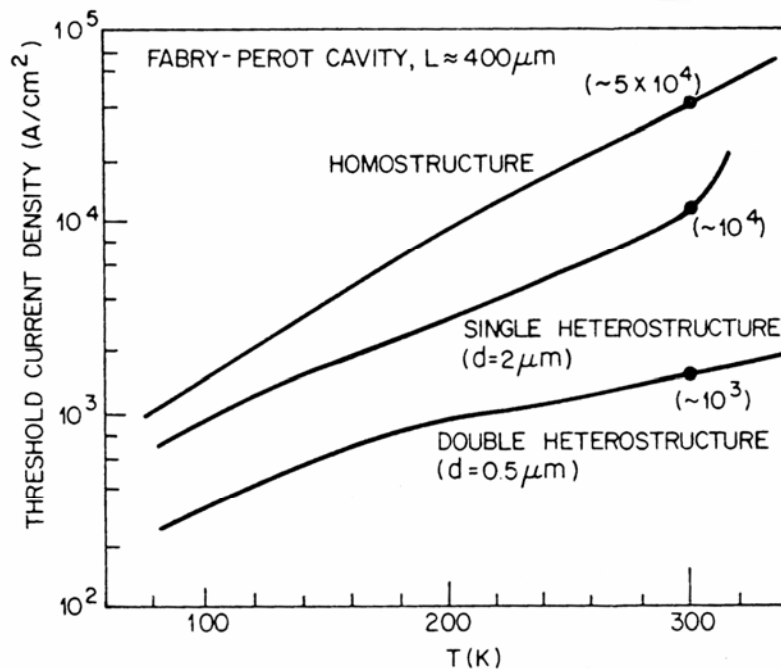


Fig. 28 Threshold current density versus temperature for three laser structures in Fig. 27. (After Panish, Hayashi, and Sumski, Ref. 48.)

Heterojunctions with Waveguides

Buried heterojunction:

- Surrounded both vertical & horizontal by lower material
- 1-2 microns wide: high efficiency, low threshold

Channeled Substrate

- Etch channel in substrate: isolate active area
- Low loss

Buried Crescent

- Fill grove to get crescent shaped active strip

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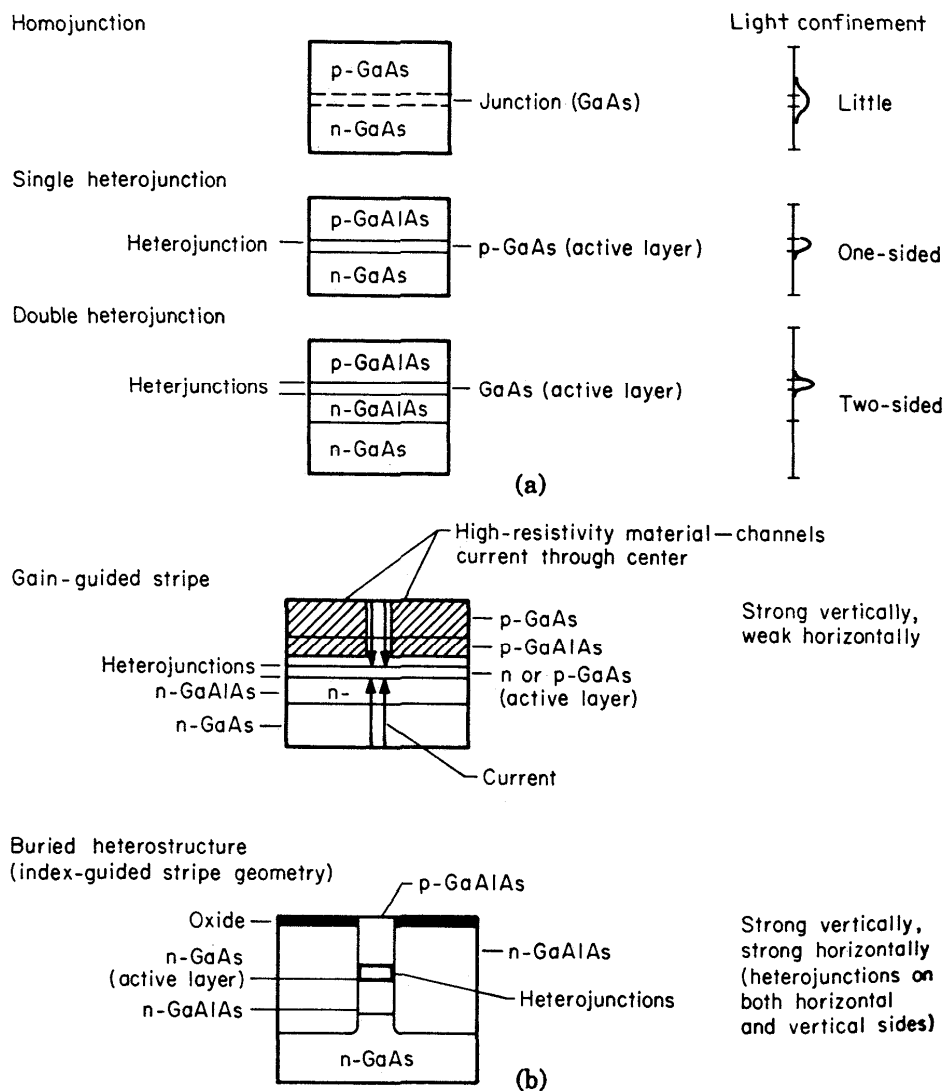


Figure 18.5 Major categories of edge-emitting diode lasers. (a) Three types shown in side views; (b) end views.

Heterojunctions with Waveguides

Ridge Waveguide

- Etch away a mesa around active region
- confines current flow to 2-3 micron strip

Double-channel planar buried heterostructure

- Isolate active with mesa, then fill with lower index
- used with very high power InGaAsP lasers

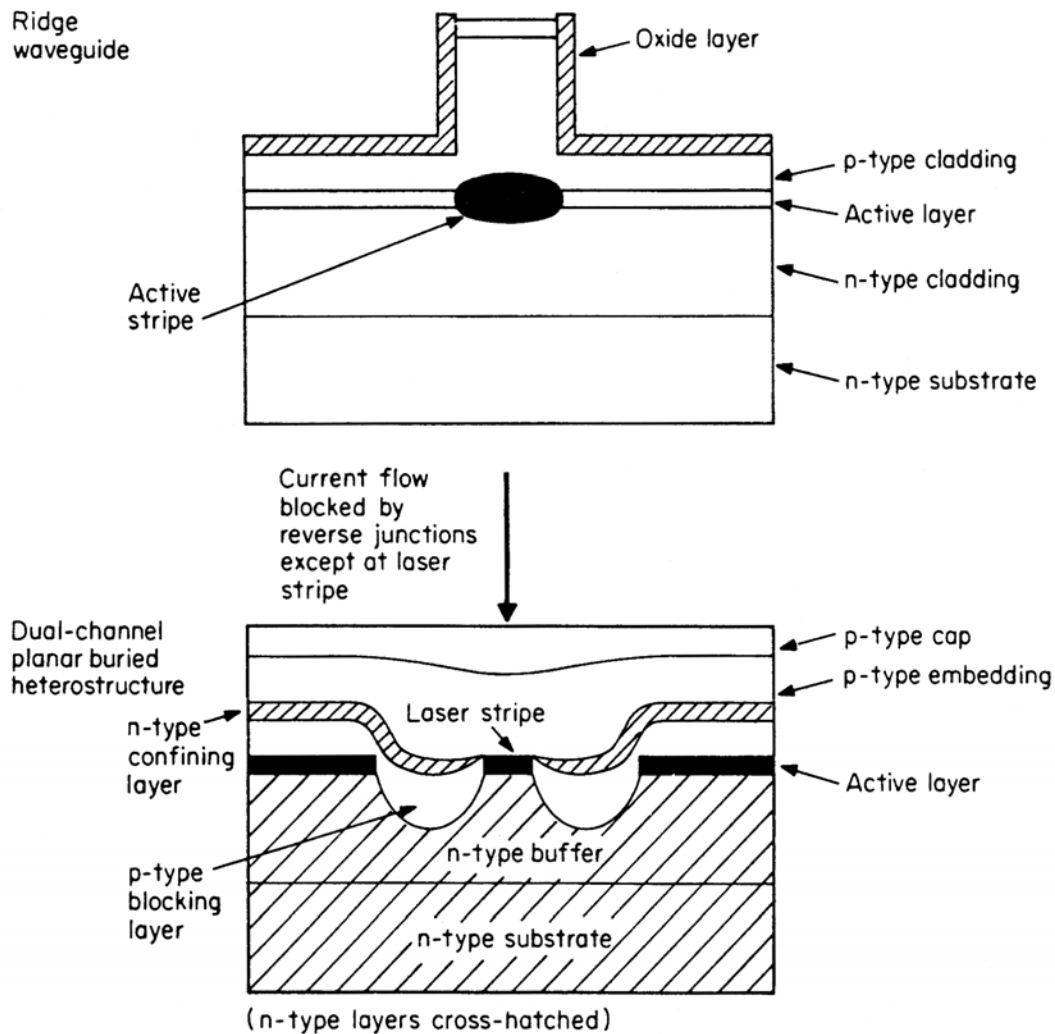


Figure 18.6 (Continued)

Quantum Well Materials

- Make layers about 20 nm thick
- Then no longer bulk materials
- Get quantum effects which change bandstructure
- Transistors still limit by the allowed momentum vectors (k)
- Now this is called Nanotechnology

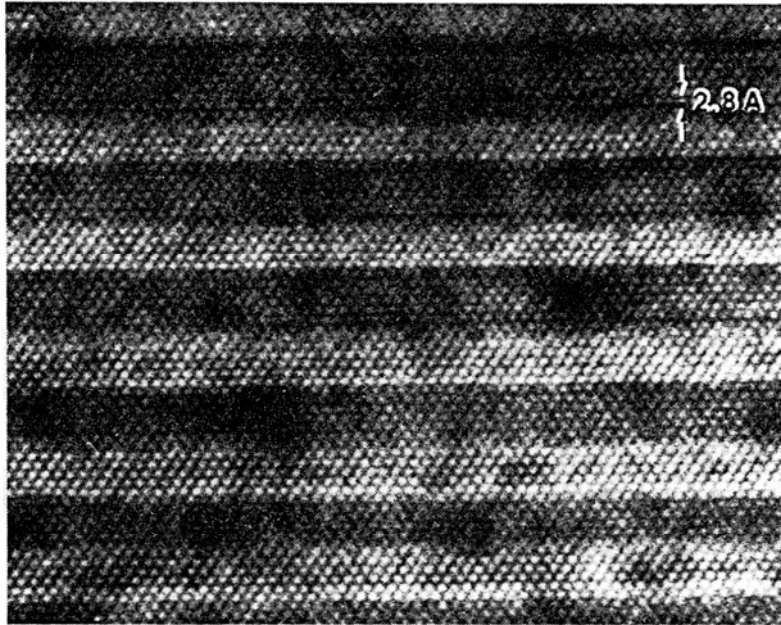
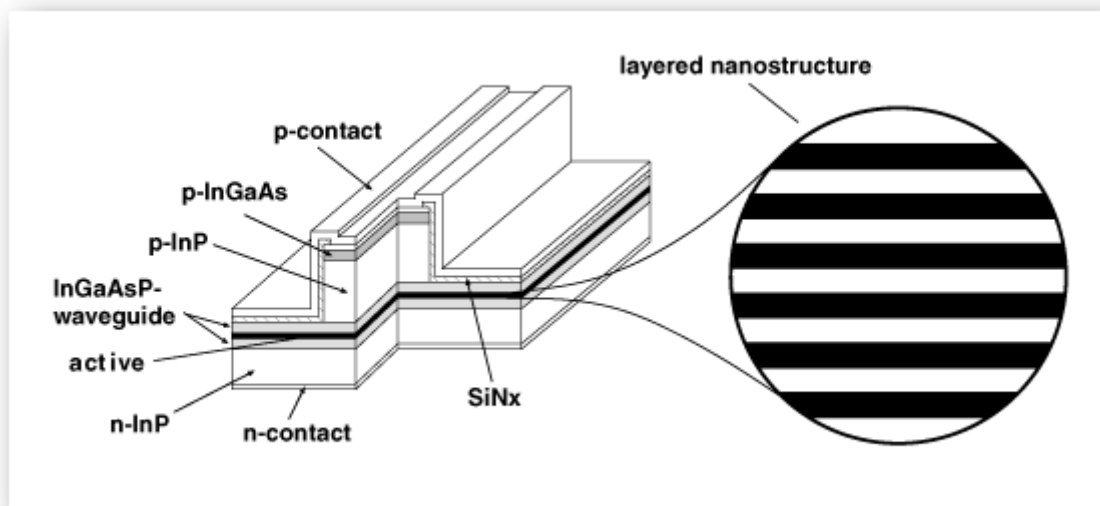


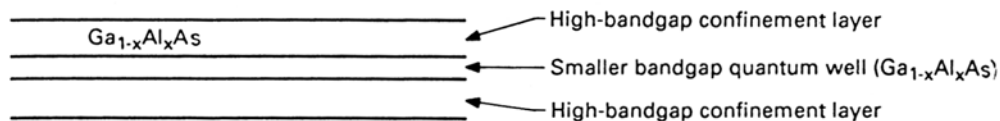
Figure 11.16 A multiple quantum well structure. This is a *transmission electron microscope* (TEM) display showing alternating layers of GaAs and $\text{Al}_x\text{Ga}_{1-x}\text{As}$ materials. Note that the transition between the materials occurs abruptly on an atomic scale. (Data provided by Prof. J. J. Coleman.)



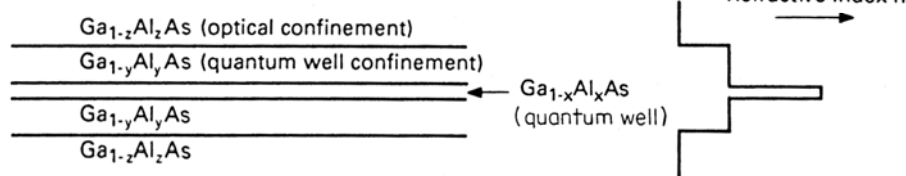
Quantum Well Lasers

- Use different layers to confine light vertically
- Confine the carriers with quantum layers
- Can use graded index of refraction materials
- Create GRINSCH laser with separate optical and carrier confinement
- Very low threshold (3 mA), high speed lasers

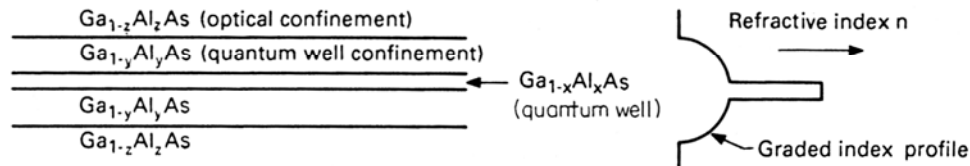
Single quantum well



Separate carrier and optical confinement heterostructure



Graded-index and separate carrier and optical confinement heterostructure (GRINSCH)



Multiple-quantum-well heterostructure

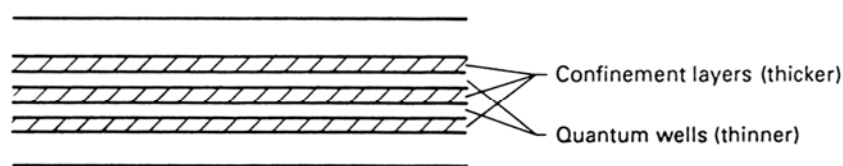
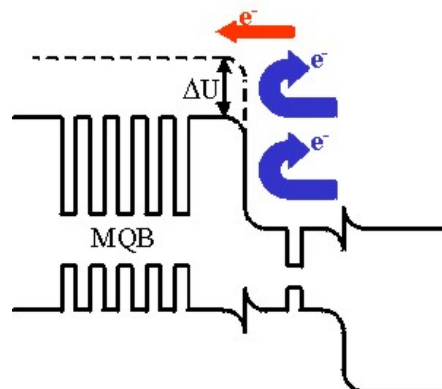
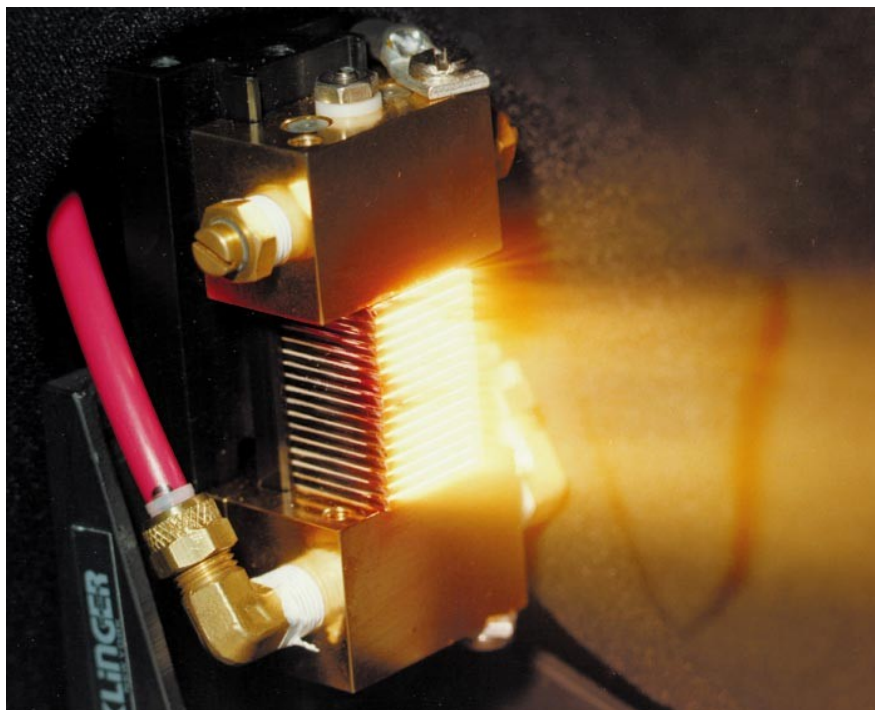
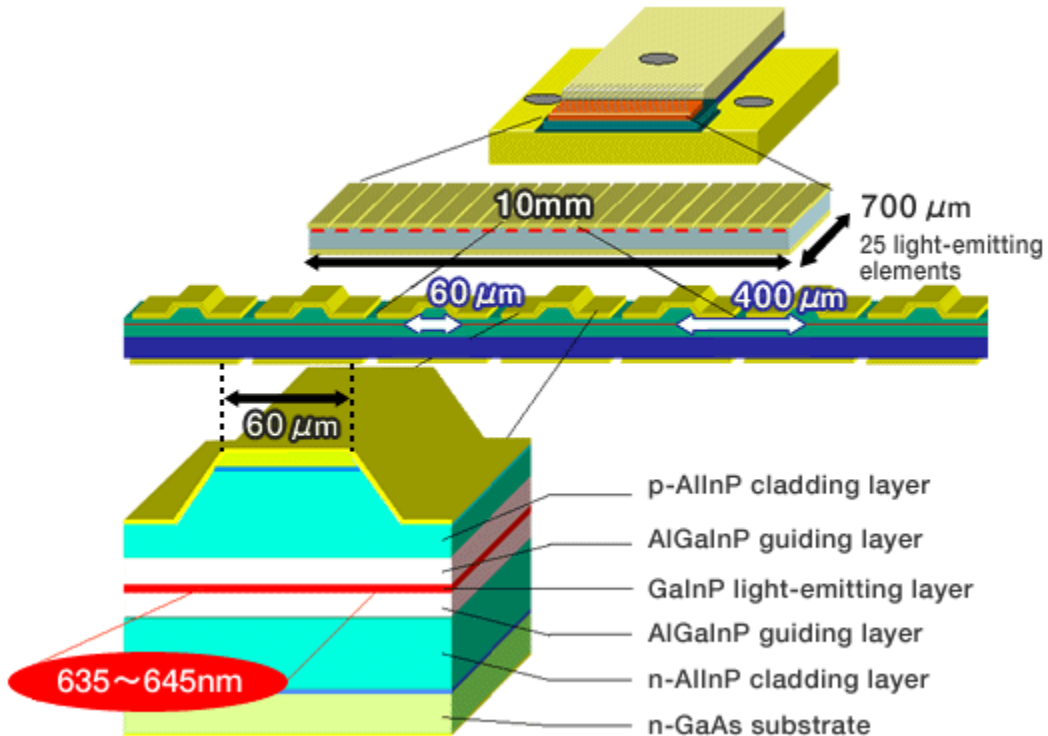


Figure 18.7 A single quantum well (top) is surrounded by thicker layers of higher-bandgap material. Forming layers with lower refractive index on top and bottom produces a separate carrier and optical confinement heterostructure (SCH). Grading the refractive index of the confinement layer produces the graded-index and separate carrier and optical confinement heterostructure (GRINSCH) laser. Multiple quantum wells also can be stacked in the active layer, as shown at bottom.



Monolithic Array Lasers

- Single strip lasers limited to 200 mW
- Many Laser strips edge emitters
- Bars with up to 200 strips produced
- 50 – 1000 W power achieved
- 20: 10 micron wide strips on 200 micron centers



Vertical Cavity Surface Emitting Lasers

- VCSEL's (Vertical Cavity Surface Emitting Lasers)
- Cavity built with doping: multilayer mirrors
- Quantum well emission layer: nearly λ in size
- Created 2 million lasers per sq. cm this way

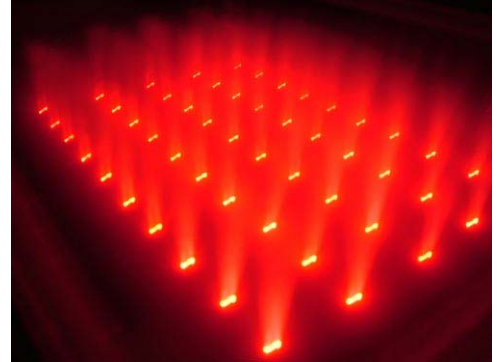
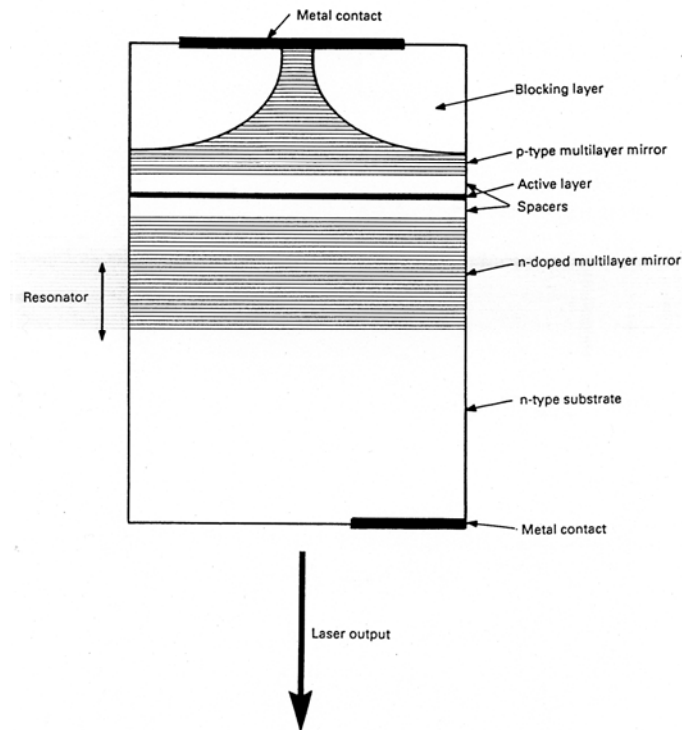
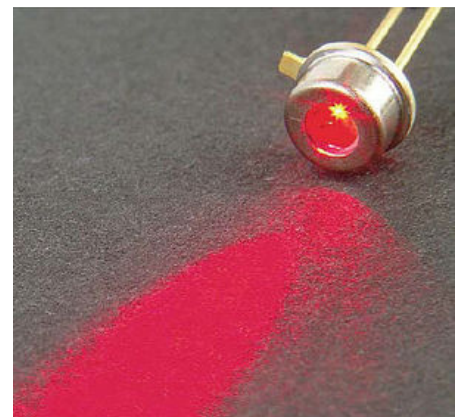
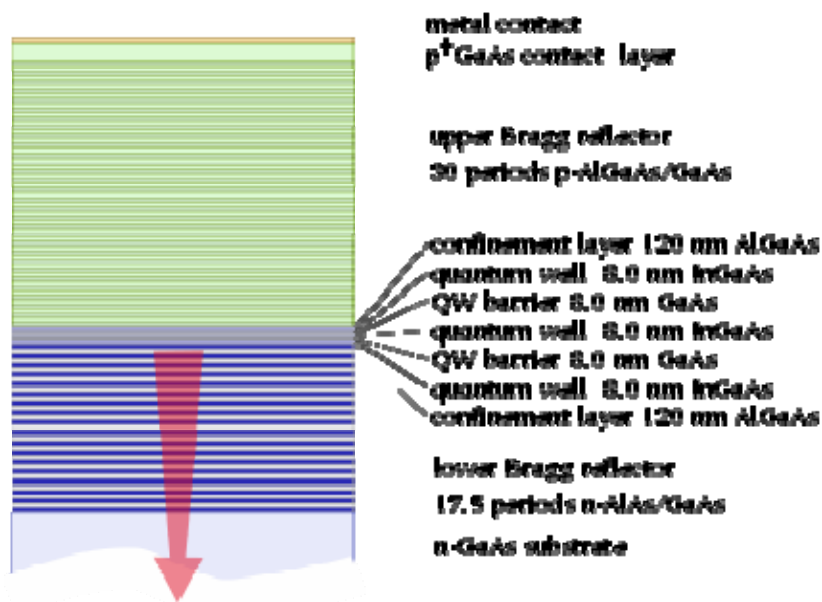
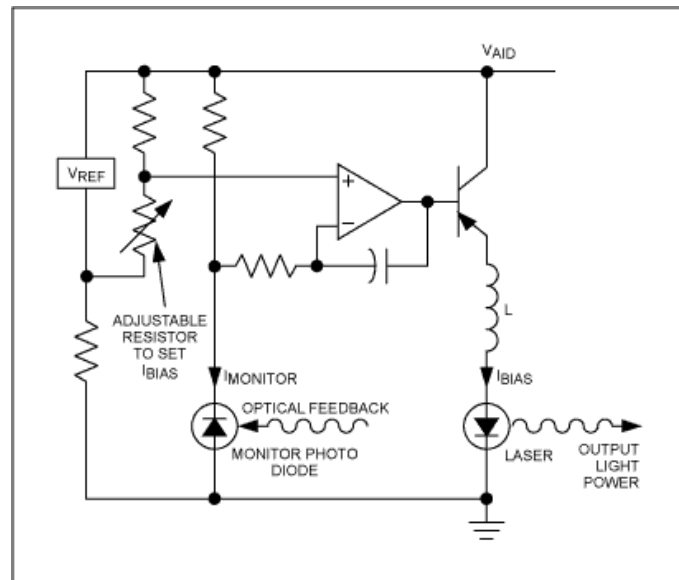


Figure 18.12 Vertical-cavity surface-emitting laser with mirrors above and below the active layer. In this version, the mirrors are multilayer structures fabricated as part of the diode structure; in other versions, one mirror may be a reflective metal or oxide film on the semiconductor surface.



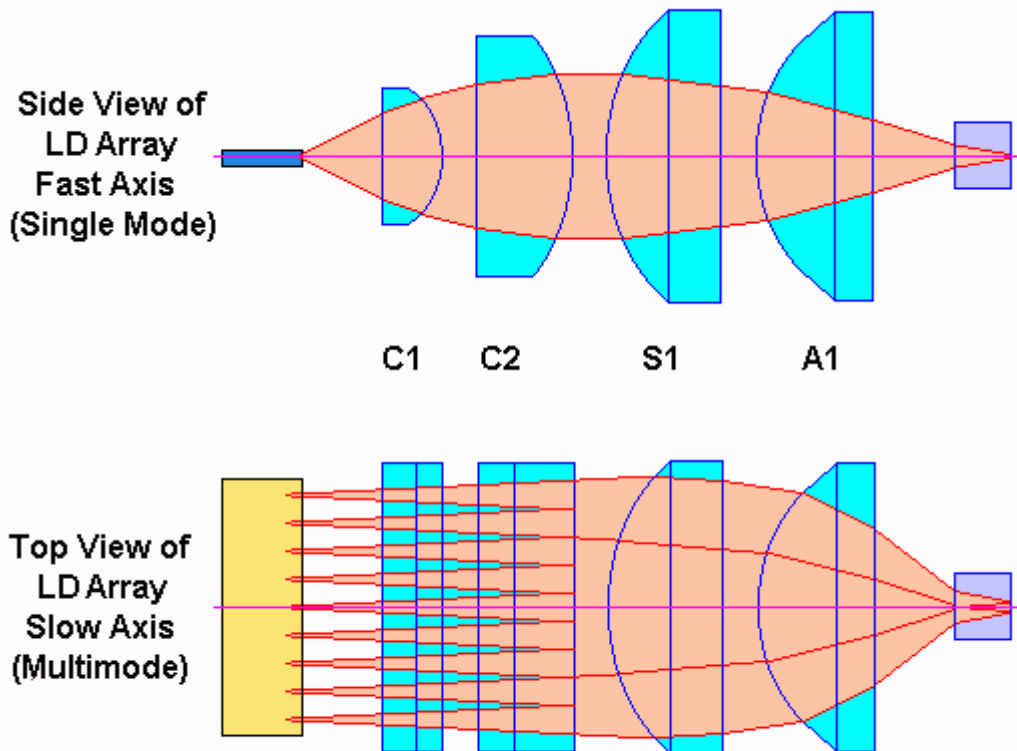
Diode Laser Power & Control

- Laser diodes are easily damaged
- As laser output increases, temperature rises, increases resistance
- Get thermal runaway
- Can permanently damage diode cleaved mirrors
- High power diodes have photodiode in same package
- Diode sees part of laser output, use feedback circuit to stabilize
- High power diodes are mounted in thermal electric cooler
- Have supply that does feedback on laser output
- Also stabilizes diode temperature with thermal cooler



Correction Diode Optics

- Laser diodes have poor output – must correct with optics
- Have fast axis (rapid expansion) – usually vertical
- Correct with high power lens
- Slow axis needs less correction, separate lens for that
- However multi-strip laser diodes cannot use single lens
- Use a microlens array for each strip
- Collimates that axis
- Use cylindrical lens arrays/lens to get both corrected
- Often spherical for fast axis, cylinder lens for slow



Laser Diode Array Beam Shaping Using Optics

Lead Salt Lasers

- Use II-VI compounds eg PbTe
- Mostly long wavelength IR lasers
- 3.3 - 29 microns

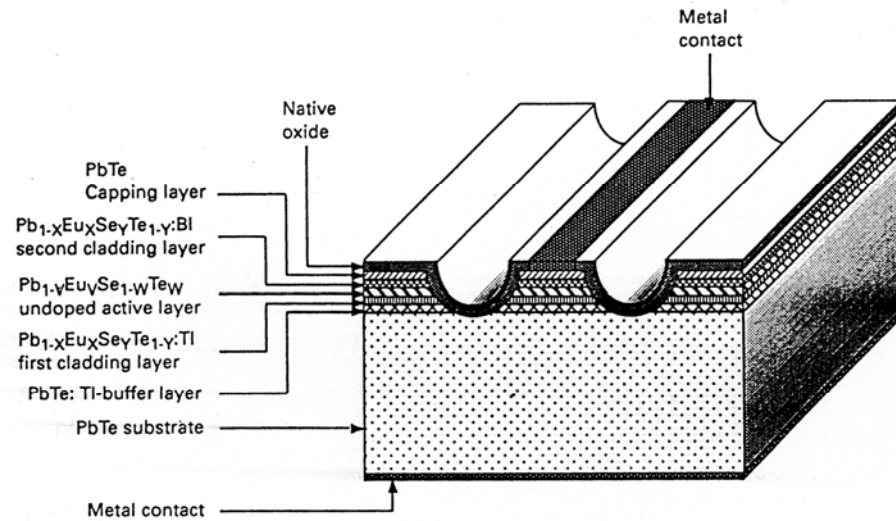


Figure 21.1 Double-channel PbEuSeTe laser with 20-μm mesa. (Courtesy of Laser Photonics Inc.)

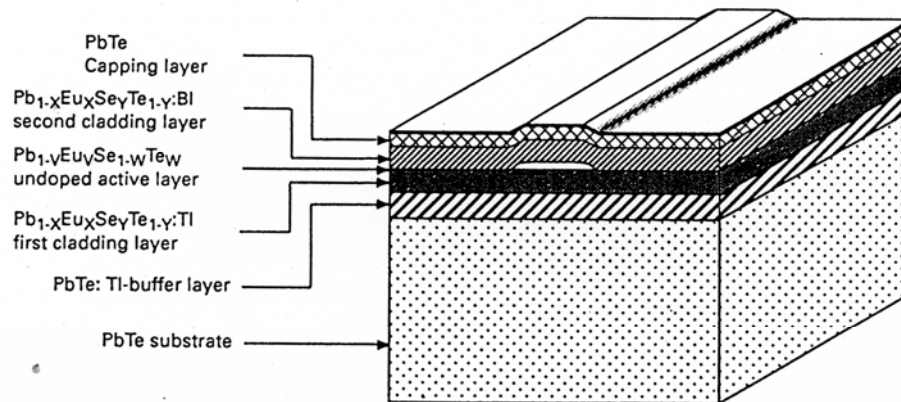


Figure 21.2 Buried-heterostructure PbEuSeTe laser with 4-μm stripe. (Courtesy of Laser Photonics Inc.)

