Metal Vapour Lasers

- Use vapourized metal as a gain medium
- Developed by W. Silfvast (1966)
- Put metal in a cavity with a heater
- Vapourize metal, then pump metal vapour with current
- Walter at TRG (1966) then developed neutral metal vapour lasers
- Two types of metal vapour lasers:
  - Ionized Metal vapour (He-Cd)
  - Neutral Metal vapour (Cu)
- All operate by vaporizing metal in container

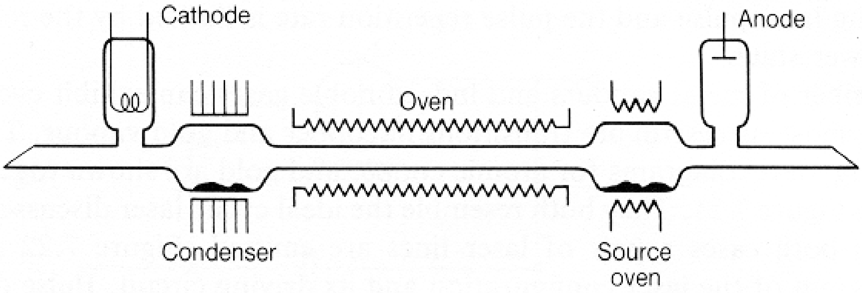


Figure 7.19 Design for discharge tube configuration used in catephoric flow He–Cd$^+$ laser.

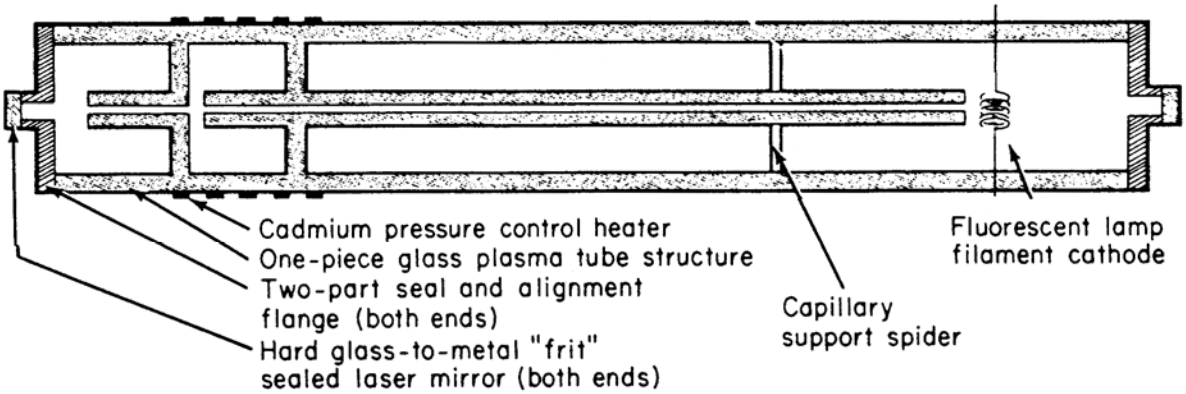


Figure 9.3 Coaxial tube design, with the bore suspended in the center of a cylindrical tube; optics are bonded directly to the tube. Helium and cadmium reservoirs are within the outer cylinder. (*Courtesy of Omnichrome.*)

Helium Cadmium Lasers

- Cadmium is heated to 250^{o}C to vaporize
- He at 3-7 torr in container
- Electrical arc eg. 1500 V, 4 A through the chamber
- Cadmium reservoir contain 1 gm Cd/1000 Hrs operation
- Must compensate for Cd ions migrating to negative electrode
- Have both side tube and coaxial designs

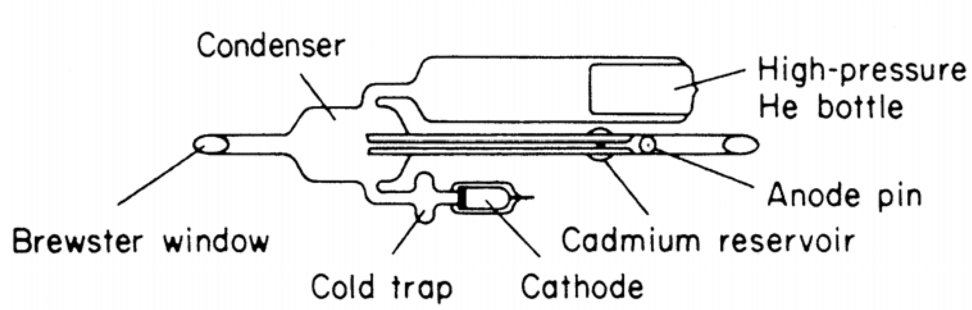
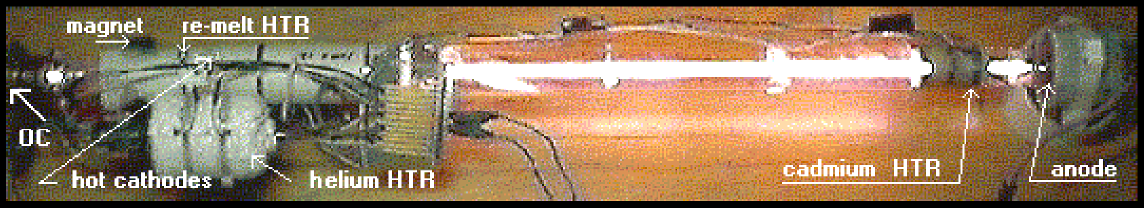


Figure 9.2 Simplified diagram of a He–Cd tube with high-pressure helium bottle to the side and a condenser and cold trap to catch cadmium metal. This tube has Brewster angle windows, but integral mirrors also can be attached. (*Courtesy of Liconix.*)



Large Omnichrome Helium-Cadmium Laser Tube

Helium Cadmium Lasers

- 3 excitement modes
- Penning ionization: He ion collides & ionizes Cd

$$He^{+} + Cd \rightarrow He + Cd^{+} + e^{-}$$

- He transfers energy to 2D Cd^{+} levels: lifetime 100 nsec
- Charge Transfer (dominant in neutral metal vapour)

$$He^{+} + Cd \rightarrow He + \left(Cd^{+}\right)^{*}$$

- Electron excitation

$$e^{-} + Cd \rightarrow Cd^{+} + 2e^{-}$$

$$e^{-} + Cd \rightarrow \left(Cd^{+}\right)^{*} + e^{-}$$

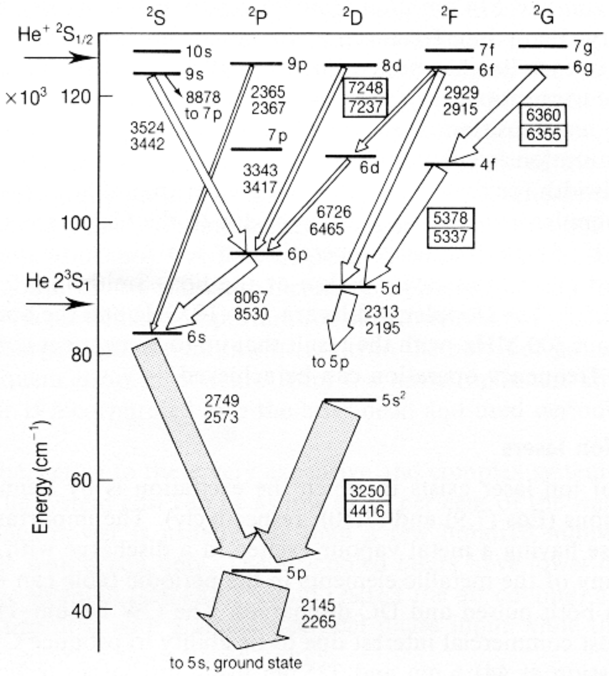


Figure 7.18 Energy diagram of the Cd^{+} ion showing the excitation routes for some laser transitions. (Data taken from Ref. 10.)

Helium Cadmium Lasers

- >12 lines available: selected by optics
  442 nm blue and 325 nm UV most important
- Can emit 636 nm red and 533.7 nm green lines also
- Used as source for Fluorescence of currency dies by US Treasury
- Slow to start due to warm up
- Generate 50 mW in TEM_{00} 150 mW in multimode, 2% efficient
- White light He-Cd mix red, green and blue to near white

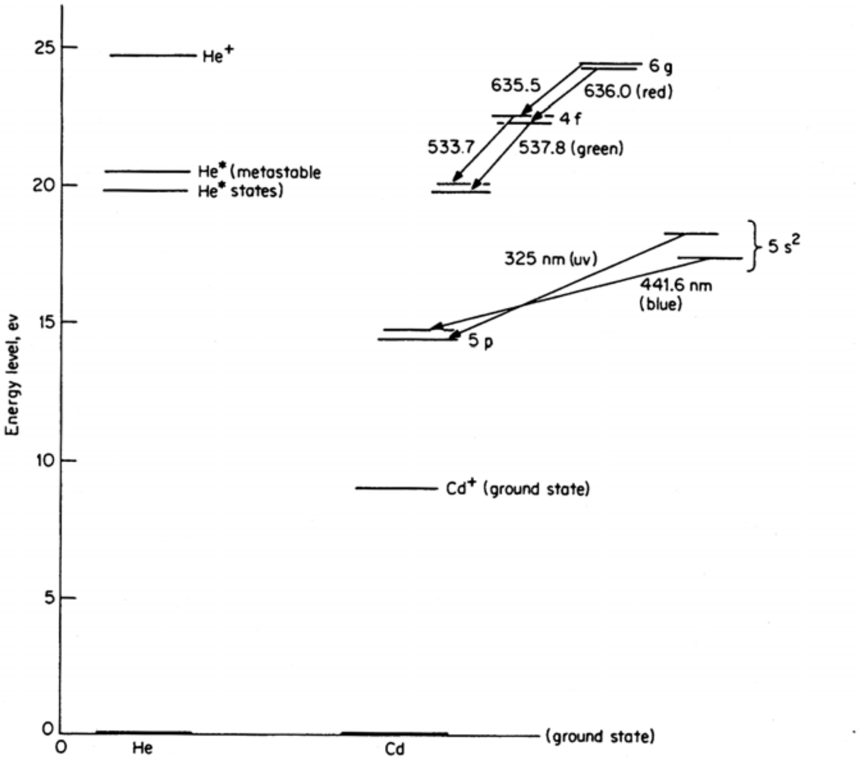


Figure 9.1 Energy levels in helium and cadmium, showing the laser transitions in the ultraviolet, blue, green, and red (wavelengths are in nanometers). The blue and ultraviolet lines are largely excited by energy transfer from the metastable helium excited states near 20 eV above ground level. Higher energy is needed to excite the red and green lines, which are emitted in a cascade process.

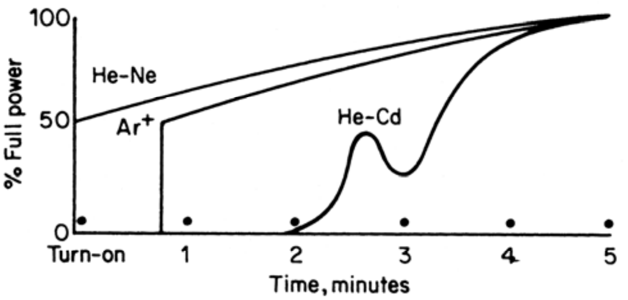


Figure 9.4 Types of power variations seen in He–Cd lasers during initial warm-up, as compared to those of He–Ne and argon ion lasers. (*Courtesy of Omnichrome.*)

Neutral Metal Vapour (Copper)

- First developed by Walter at TRW 1966
- Require vaporized metal: 1500 - 1800 ^{o}C
- creates 0.1 torr of metal gas pressure
- Copper and Gold most common types

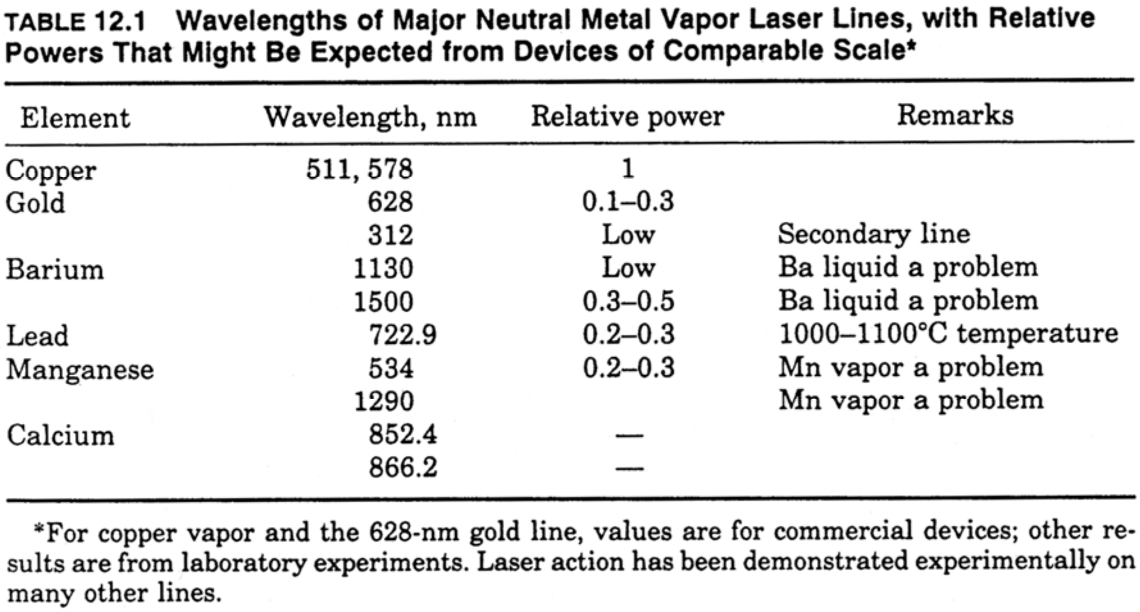


TABLE 12.1 Wavelengths of Major Neutral Metal Vapor Laser Lines, with Relative Powers That Might Be Expected from Devices of Comparable Scale*

Element	Wavelength, nm	Relative power	Remarks
Copper	511, 578	1	
Gold	628	0.1–0.3	
	312	Low	Secondary line
Barium	1130	Low	Ba liquid a problem
	1500	0.3–0.5	Ba liquid a problem
Lead	722.9	0.2–0.3	1000–1100°C temperature
Manganese	534	0.2–0.3	Mn vapor a problem
	1290		Mn vapor a problem
Calcium	852.4	—	
	866.2	—	

*For copper vapor and the 628-nm gold line, values are for commercial devices; other results are from laboratory experiments. Laser action has been demonstrated experimentally on many other lines.

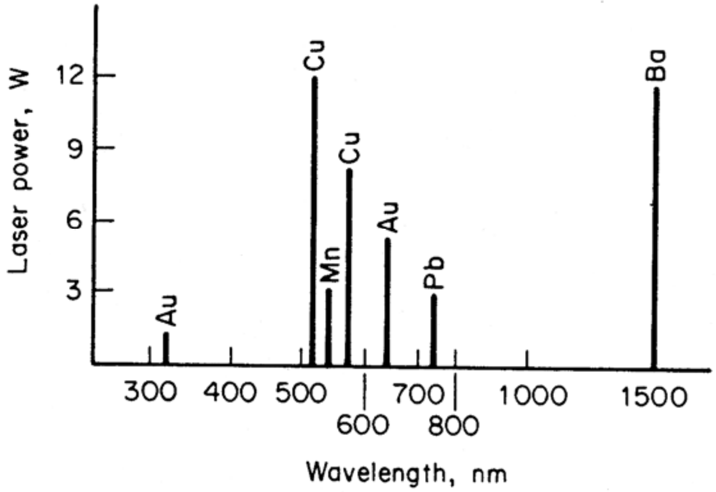


Figure 12.3 Wavelengths and relative intensities of some major neutral metal vapor laser lines. (*Courtesy of Quentron Optics Pty. Ltd.*)

Copper Vapour Lasers

- Use electrical arc to excite vapour
- Add Neon at 25 torr to improve discharge
- Electron or ion collision excite Cu
- Upper state 10 msec metastable lifetime
- Emit at 510.6 green and 578 nm yellow lines
- Pulsed: 100 nsec

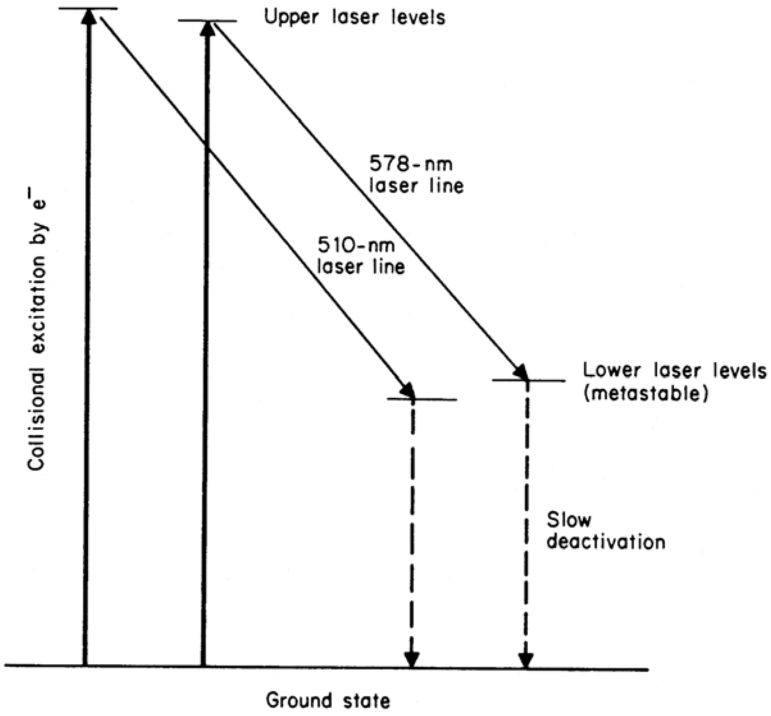
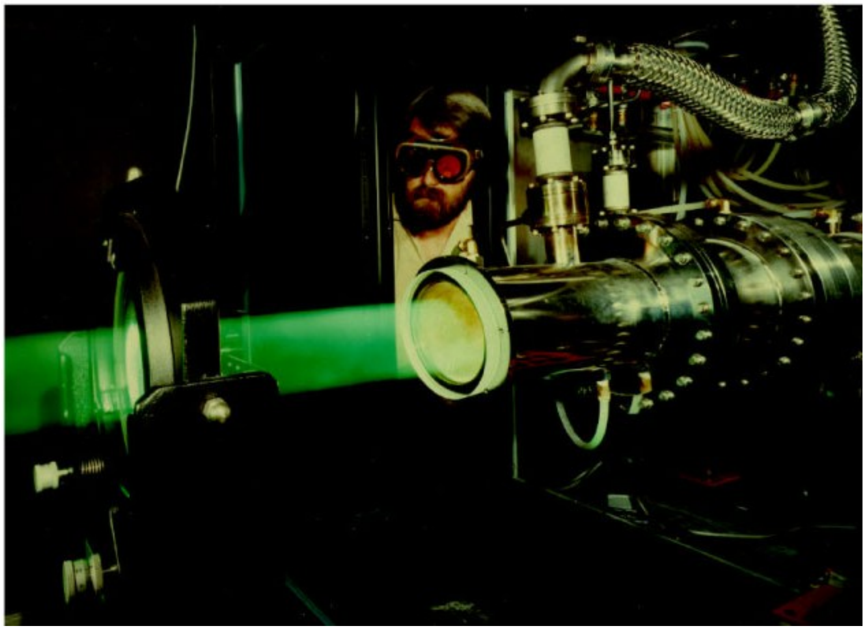


Figure 12.1 Energy levels and laser transitions in copper vapor.

COPPER VAPOR LASER



Copper Metal Vapour & Isotope Separation

- Ratio of lines in Cu laser depends on temperature
- Commercial application to pump dye lasers for photochemistry
- Major application: Atomic Vapor Laser Isotope Separation AVLIS
- Isotopes: same element, different number of neutrons in nucleus
- Thus different atomic weight but same atomic number
- Eg. Uranium: U^{238} does not fission but 99.3% of U in earth
- U^{235} which fissions for atomic bombs or reactors 0.71%
- Need to enrich amount of U^{235} for light water reactors (~1-4%)
- Atomic bombs need ~98% U^{235}
- Different isotopes have slightly different wavelengths
- Tune laser to ionize one isotope (U235) but not others
- Then E field can separate ionized from unionized vapour
- Get several % enrichment per attachment
- U^{235} and Pu^{239} separation
- Lawrence Livermore Labs major Developer: cancelled 1999

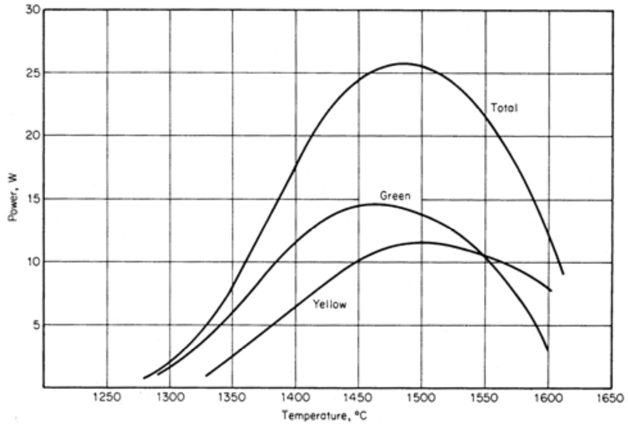
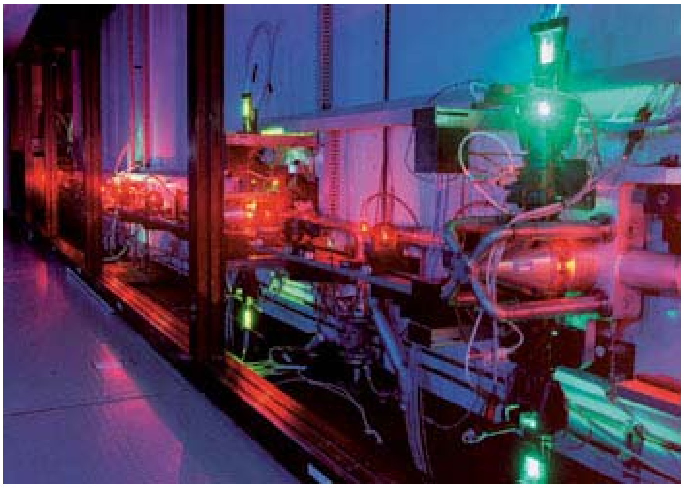
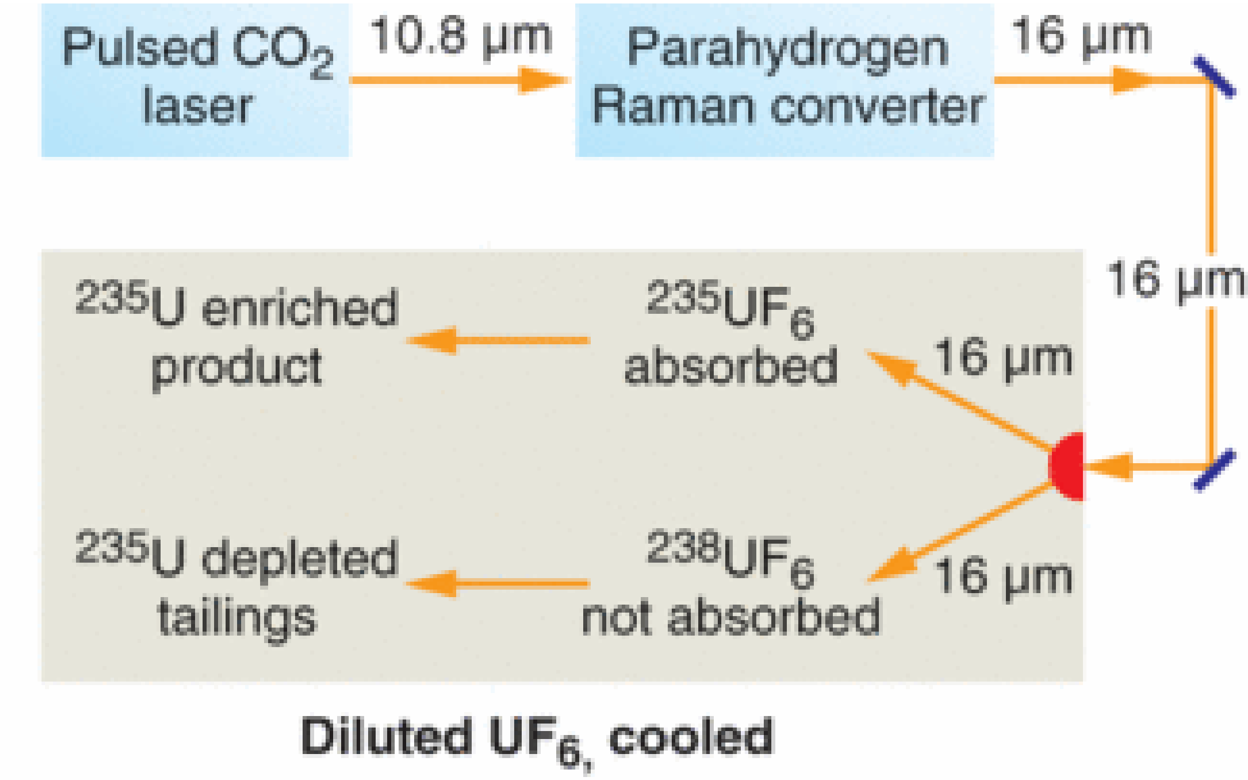


Figure 12.2 Relative strengths of copper vapor lines as a function of temperature. *(Courtesy of Oxford Lasers Ltd.)*



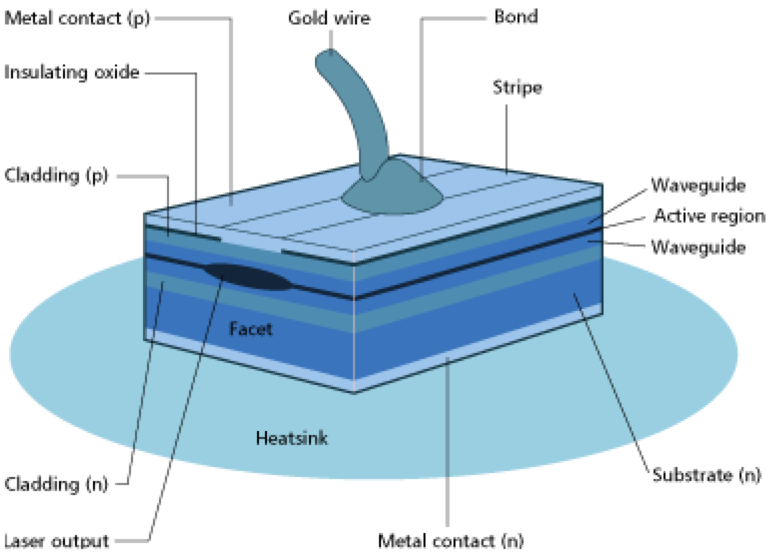
Silex: Newest Laser Uranium Enrichment

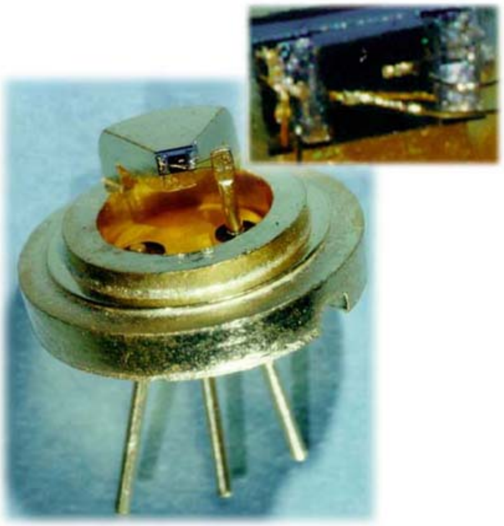
- Laser U enrichment advance is the Silex process
- Developed in Australia ~2000
- Uses modified CO_2 laser to pump parahaydrogen
- Parahydrogen is H where the spins are aligned
- Creates 16 um long wavelength that is absorbed by $U^{235}F_6$
- Separates the isotopes

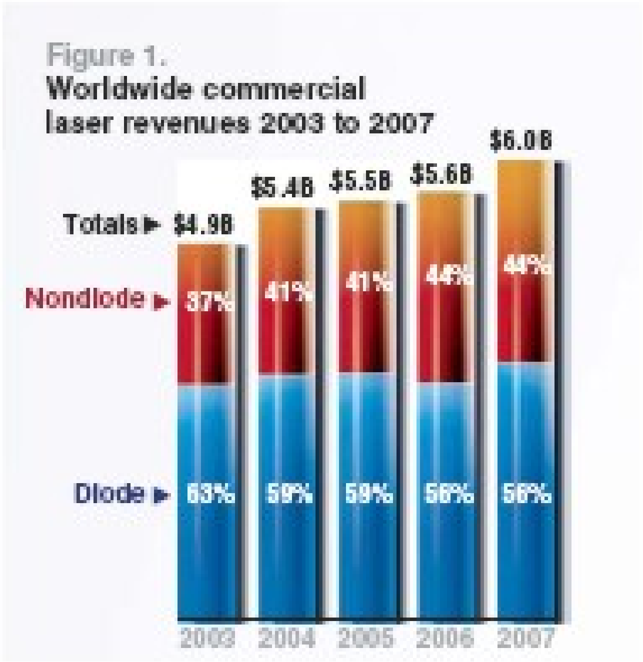


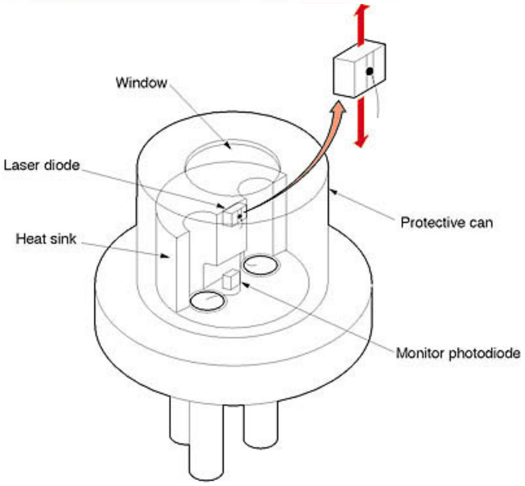
Semiconductor Lasers

- 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 – 56% of market sales
- Driven by small size, high efficiently, 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 Bandbap
- Conversion efficiency ~3x greater

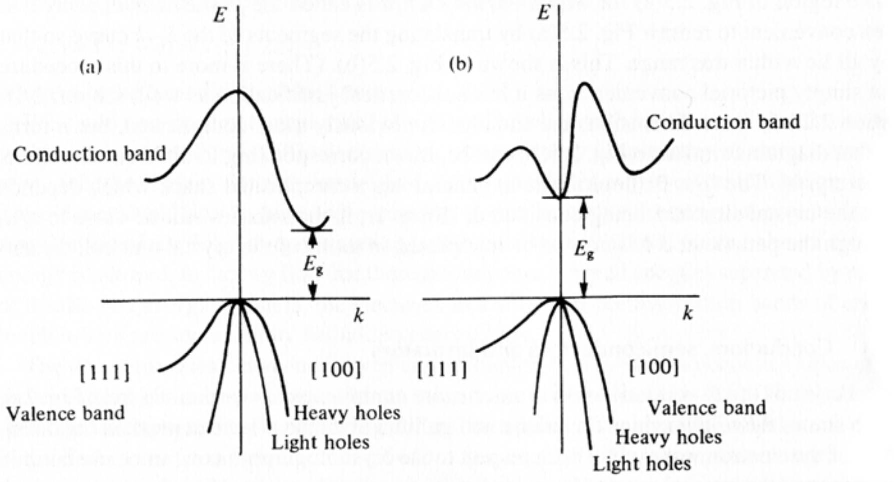


FIG. 2.6 Relationship of E–k for real solids: (a) silicon (which has an indirect bandgap) and (b) gallium arsenide (which has a direct bandgap). The figure shows the conduction and valence bands and the energy gap E_g between them. Note that (i) k is specified in different crystallographic directions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

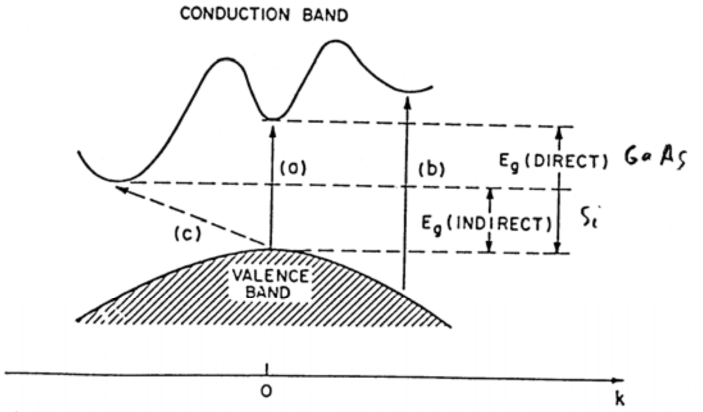


Fig. 26 Optical transitions: (*a*) and (*b*) direct transitions; (*c*) indirect transition involving phonons.

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

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

h = 4.13 x 10^{-15} eV
hc = 1.24 μm eV

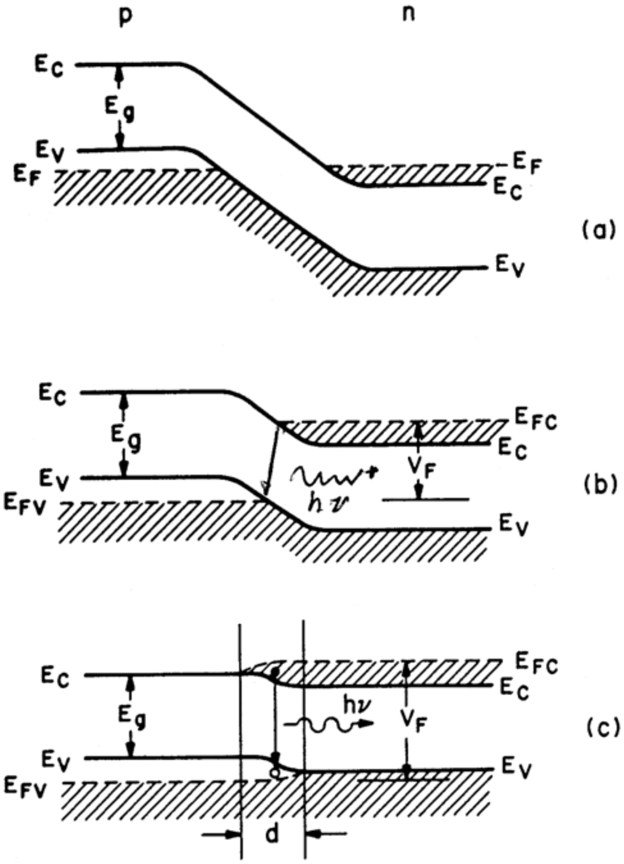


Fig. 19 Energy band diagrams of a degenerate *p–n* junction (*a*) at thermal equilibrium, (*b*) under forward bias, and (*c*) under high-injection condition.

Luminescent Efficiency

- Radiative processes: emitt light
- Non-Radiative processes: produce phonons (accoustic packets) & heat
- Quantum efficiency η_q: fraction of carriers combining radiatively

$$\eta_q = \frac{R_r}{R_t} = \frac{\tau_r}{(\tau_{nr} + \tau_r)}$$

where τ = lifetime: r = radiative, nr = non-radiative
R = recombination rate: r = radiative, t = total

- In p regions then

$$R = \frac{n - n_0}{\tau}$$

where $n - n_0$ = injected carrier density

$$\tau = \frac{\tau_r \tau_{nr}}{(\tau_{nr} + \tau_r)} \quad or \quad \frac{1}{\tau} = \frac{1}{\tau_r} + \frac{1}{\tau_{nr}}$$

- Efficiency can approach 1 in modern LED's

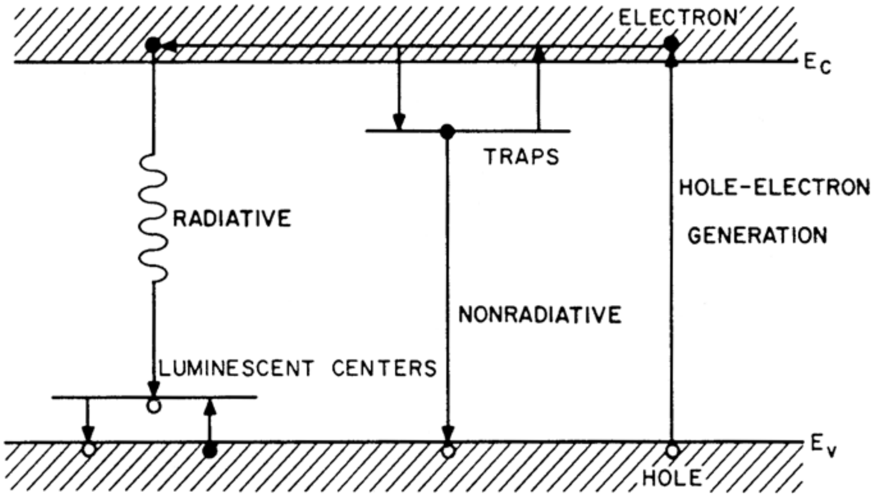


Fig. 4 Representation of radiative and nonradiative recombinations. (After Ivey, Ref. 26.)

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

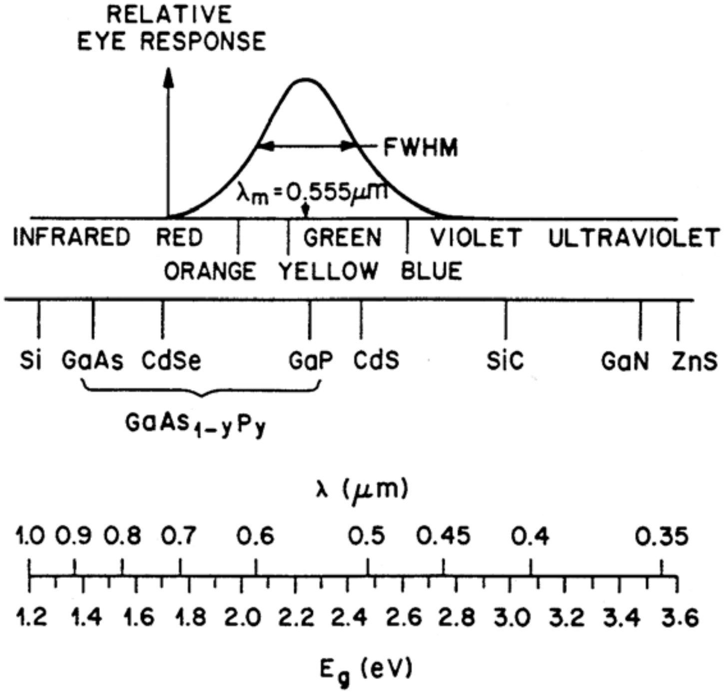


Fig. 6 Semiconductors of interest as visible LEDs. Figure includes relative response of the human eye.

Quaternary and Pentenary Alloy systems

- Can mix both III and V compounds or higher
- Gives much more freedom in Bandgap & Lattice
- Common Examples
  - $Ga_xIn_{1-x}As_yP_{1-y}$
  - $Al_xGa_{1-x}As_ySb_{1-y}$
- Extreme example uses I-III-VI compounds
  - $Cu_xAg_{1-x}InS_{2y}Se_{2(1-y)}$

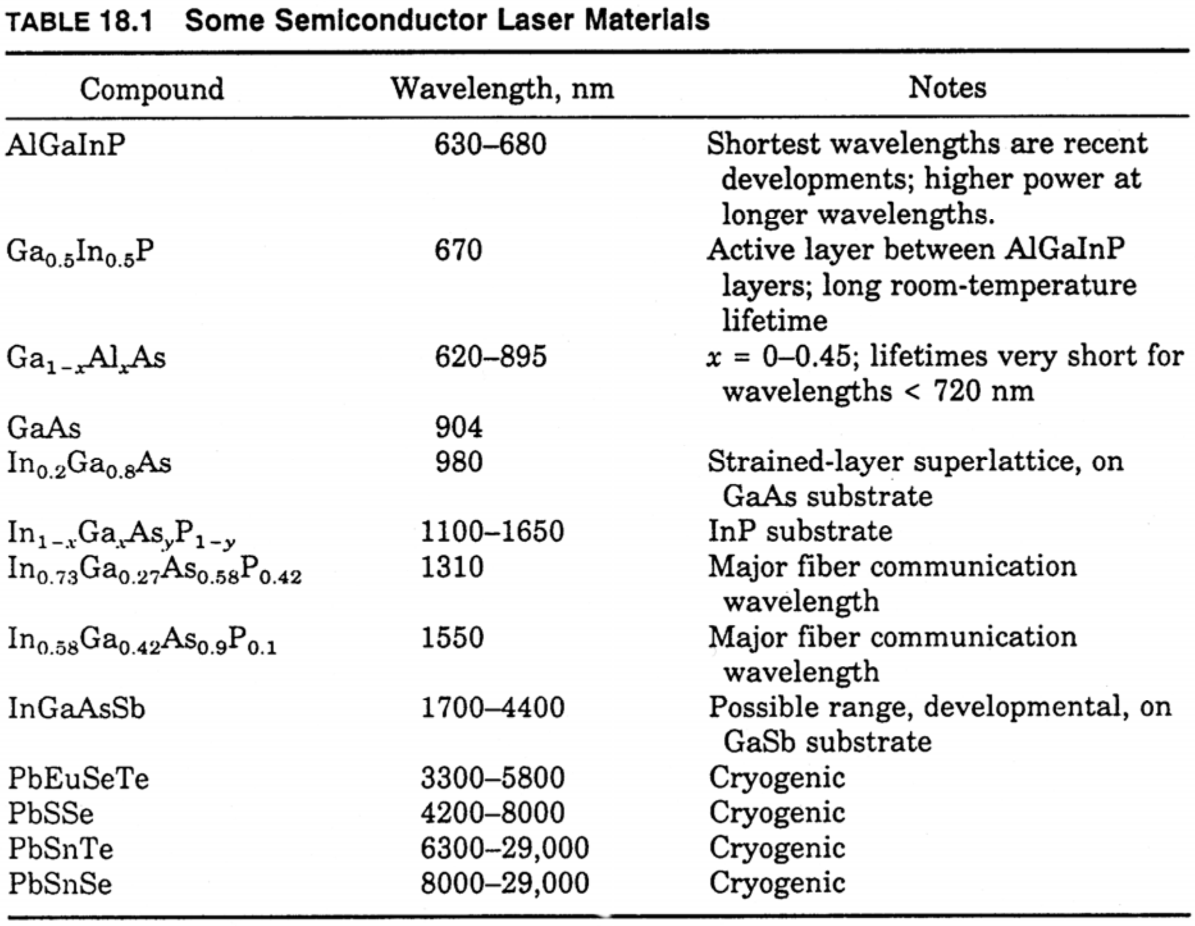


TABLE 18.1 Some Semiconductor Laser Materials

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
$Ga_{1-x}Al_xAs$	620–895	$x = 0$–0.45; lifetimes very short for wavelengths < 720 nm
GaAs	904	
$In_{0.2}Ga_{0.8}As$	980	Strained-layer superlattice, on GaAs substrate
$In_{1-x}Ga_xAs_yP_{1-y}$	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

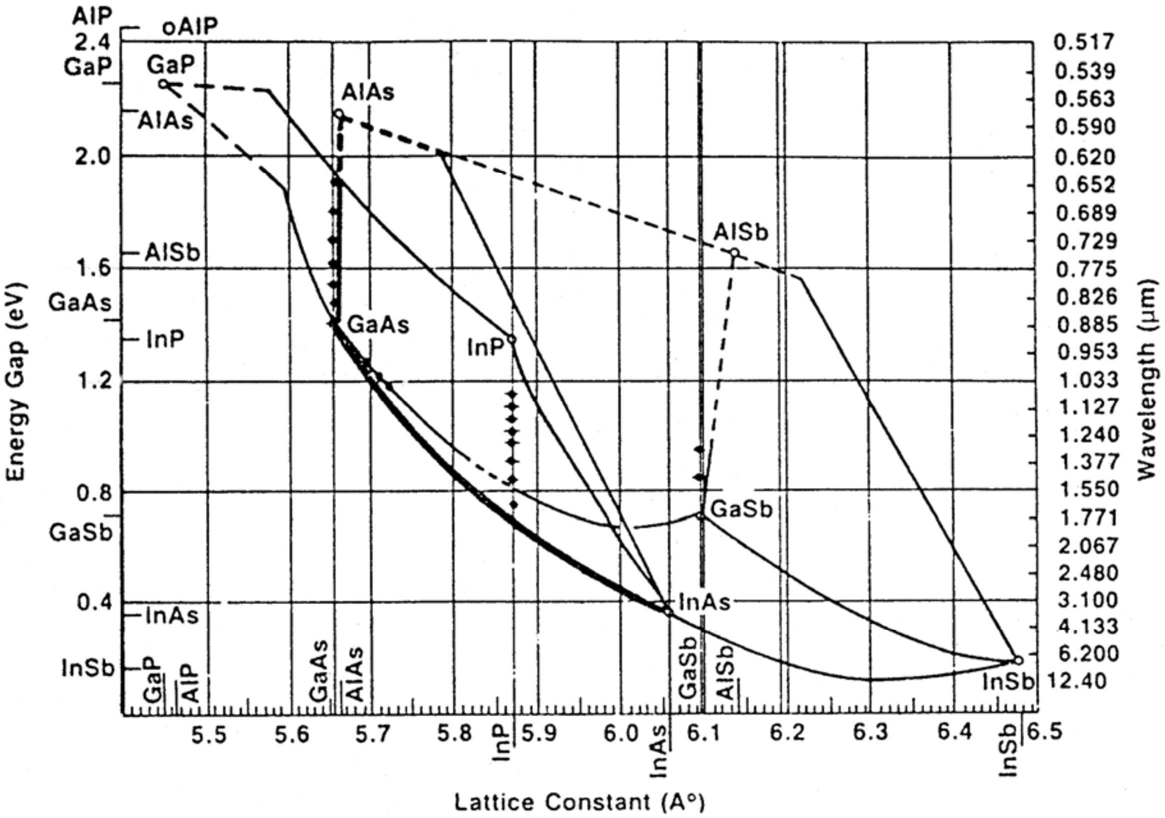


Figure 19.3 Energy bandgap and lattice constants for III to V bulk semiconductors. Dashed lines indicate indirect-bandgap materials not suitable for laser operation; solid lines are direct-bandgap materials. Lines that connect points for binary compounds represent values of intermediate ternary compounds; 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*]

Optical Light Confinement

- When first tired could only lase when cooled below 77^{o}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

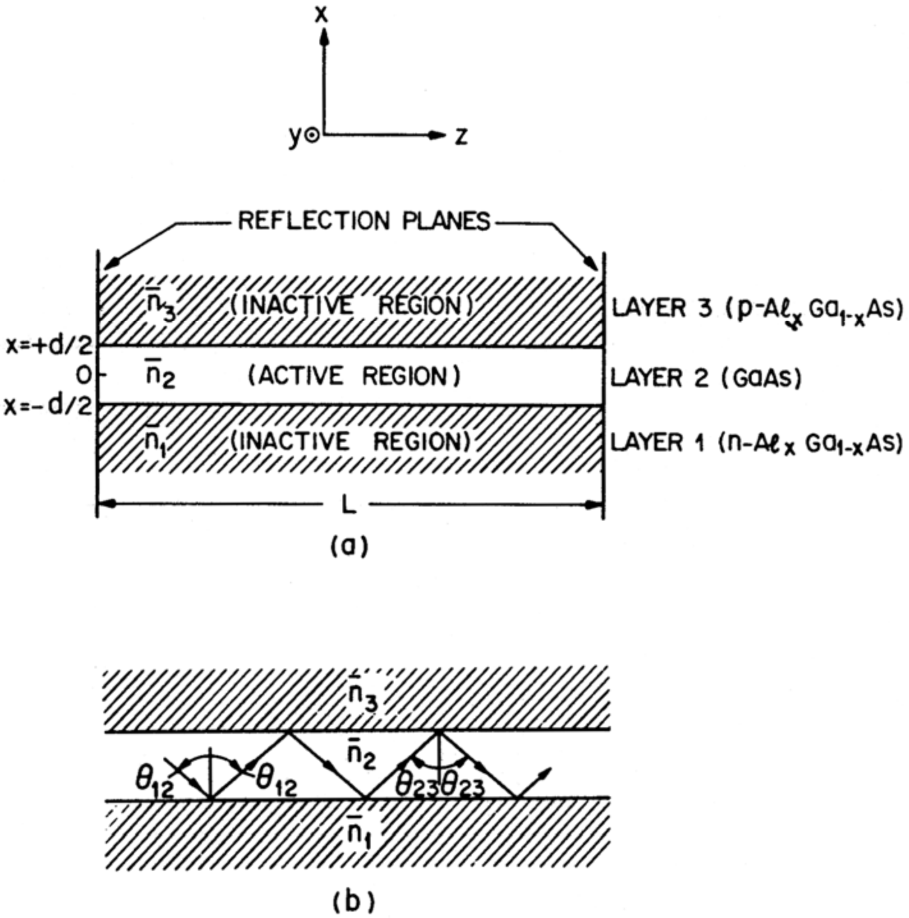


Fig. 29 (*a*) Representation of a three-layer dielectric waveguide. (*b*) Ray trajectories of the guided wave.

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

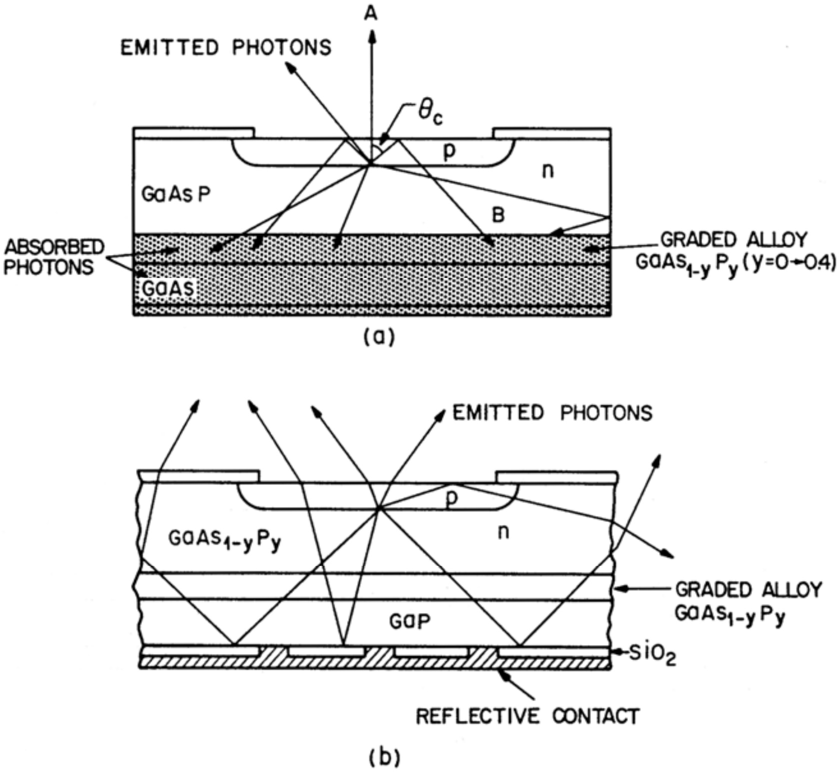
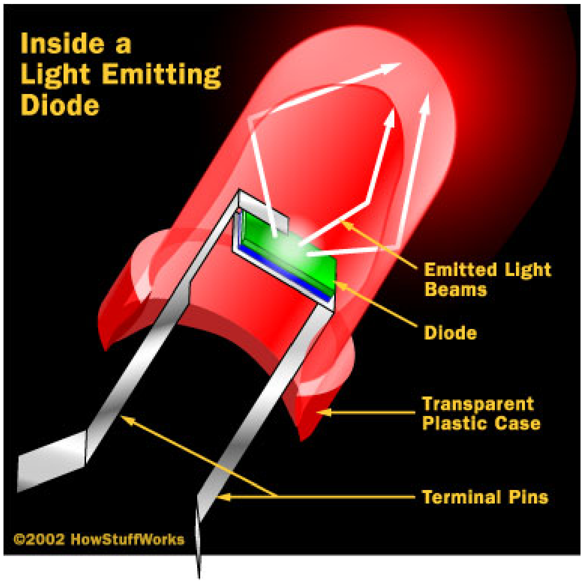
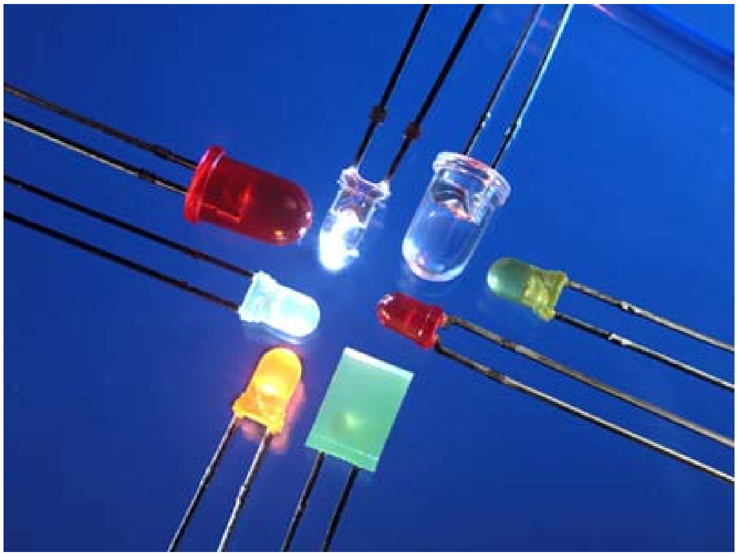


Fig. 9 Effects of (*a*) opaque substrate and (*b*) transparent substrate on photon emitted at the *p*–*n* junction.[6]





PN Junction Diode Laser

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

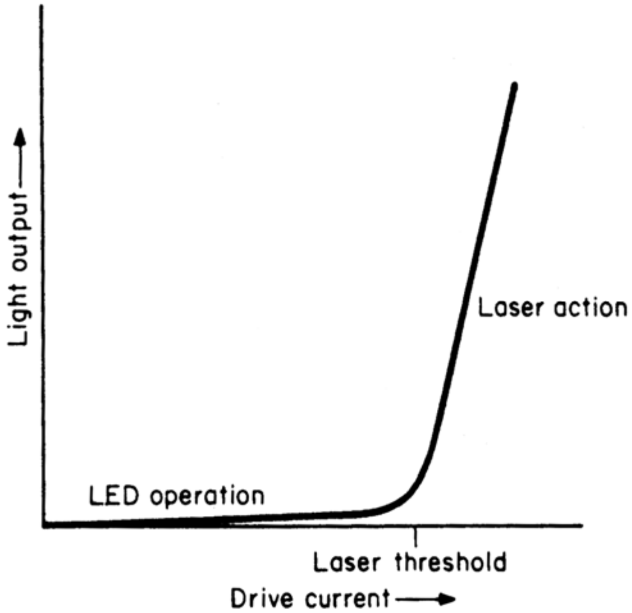


Figure 18.3 Output of a laser diode below threshold (when it operates as an LED) and above threshold (when it operates as a laser). The much steeper slope for laser operation indicates higher-efficiency emission.

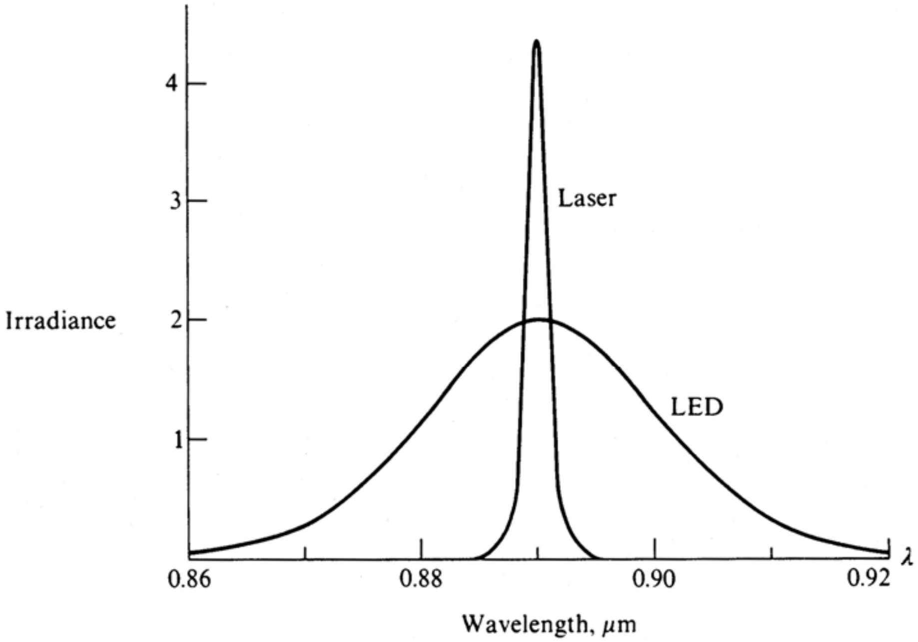


Fig. 6.25 Emission spectrum of a semiconductor laser compared to that of an LED operating below threshold.

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 Ellipitical emission: 1x50 microns
- Problem: light not vertically confined
  Hence requires very high threshold current & device cooling
  Often only operates as laser at Liquid Nitrogen temp (77^{o}K)
- Homojunction where first type of laser diodes
- Hetrojunction better: P and N materials different

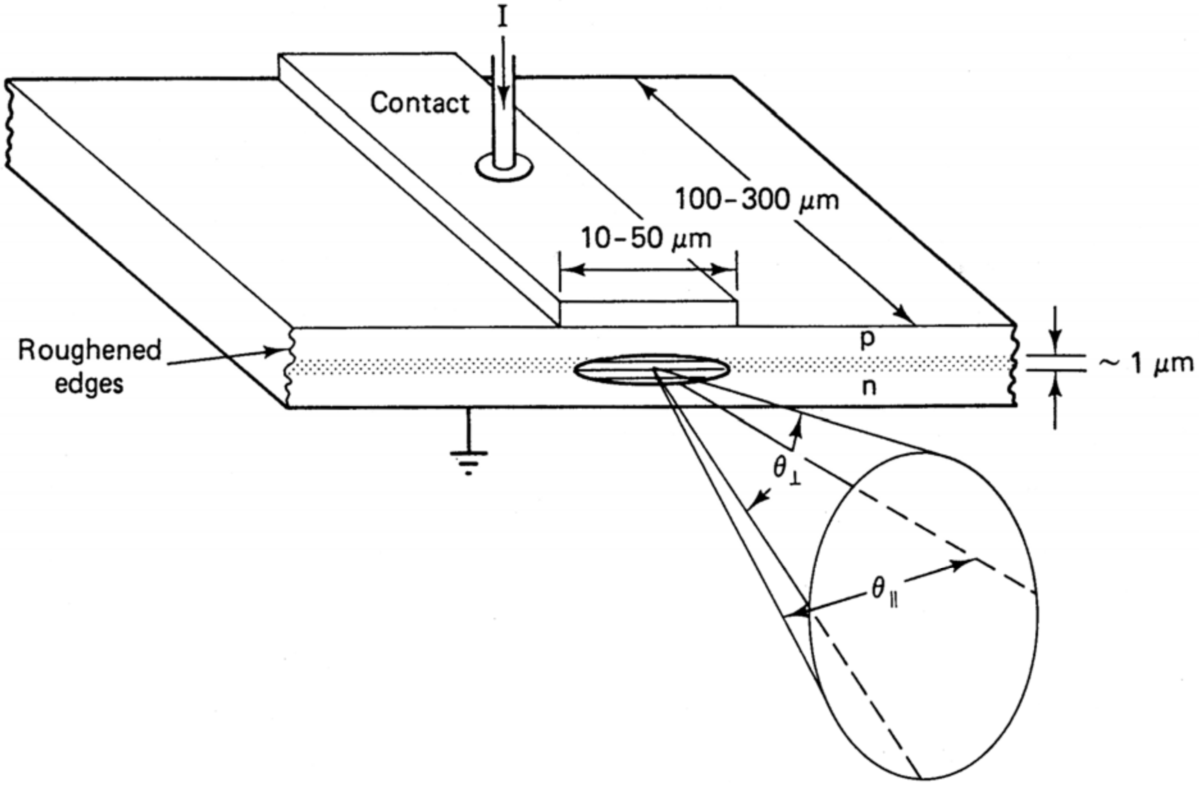


Figure 11.11 The radiation field of a semiconductor laser.

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

  $Al_xGa_{1-1}As$
- x = mole fraction of Aluminum
- 1-x = mole fraction of Gallium

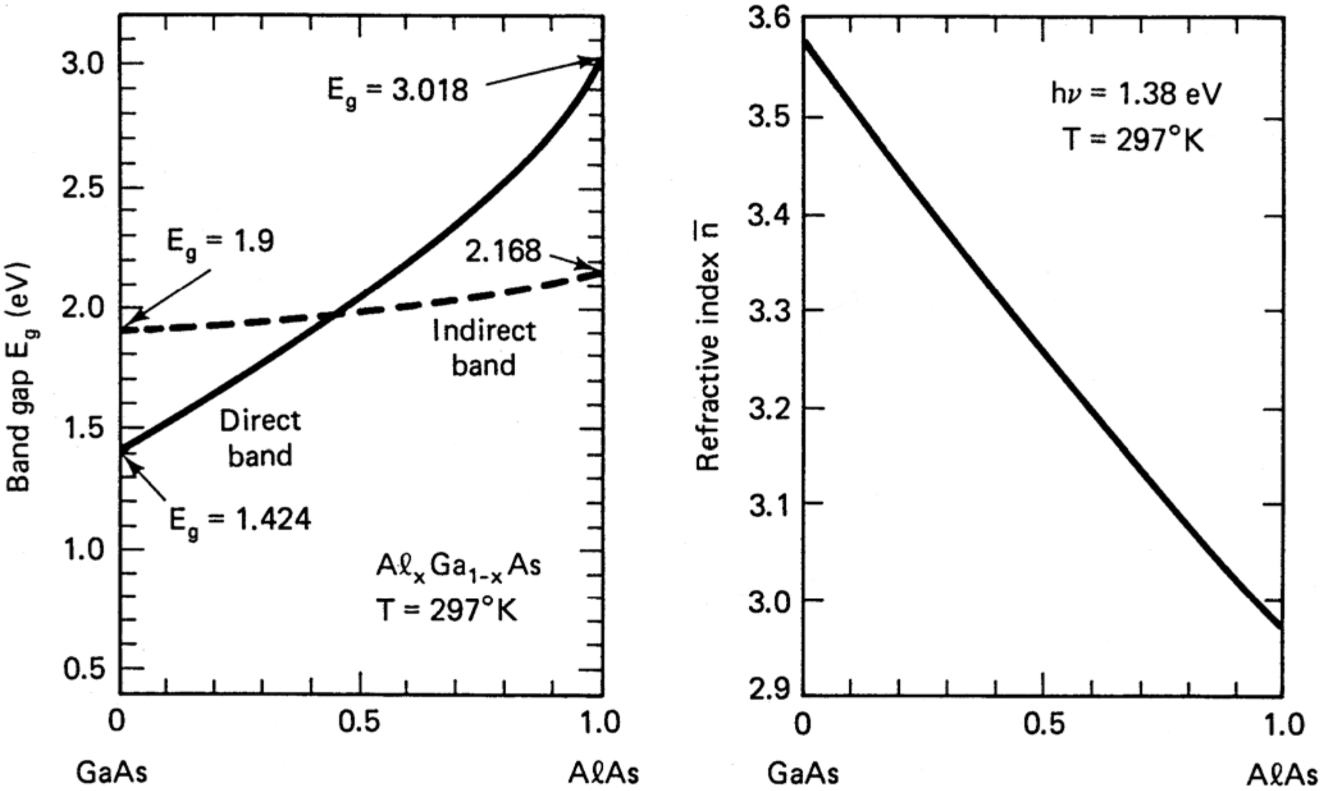


Figure 11.12 Mole fraction AℓAs, x. Dependence of the band gap and index of refraction of $Al_xGa_{1-x}As$ on the amount of aluminum. (Data from Casey and Panish.[22])

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

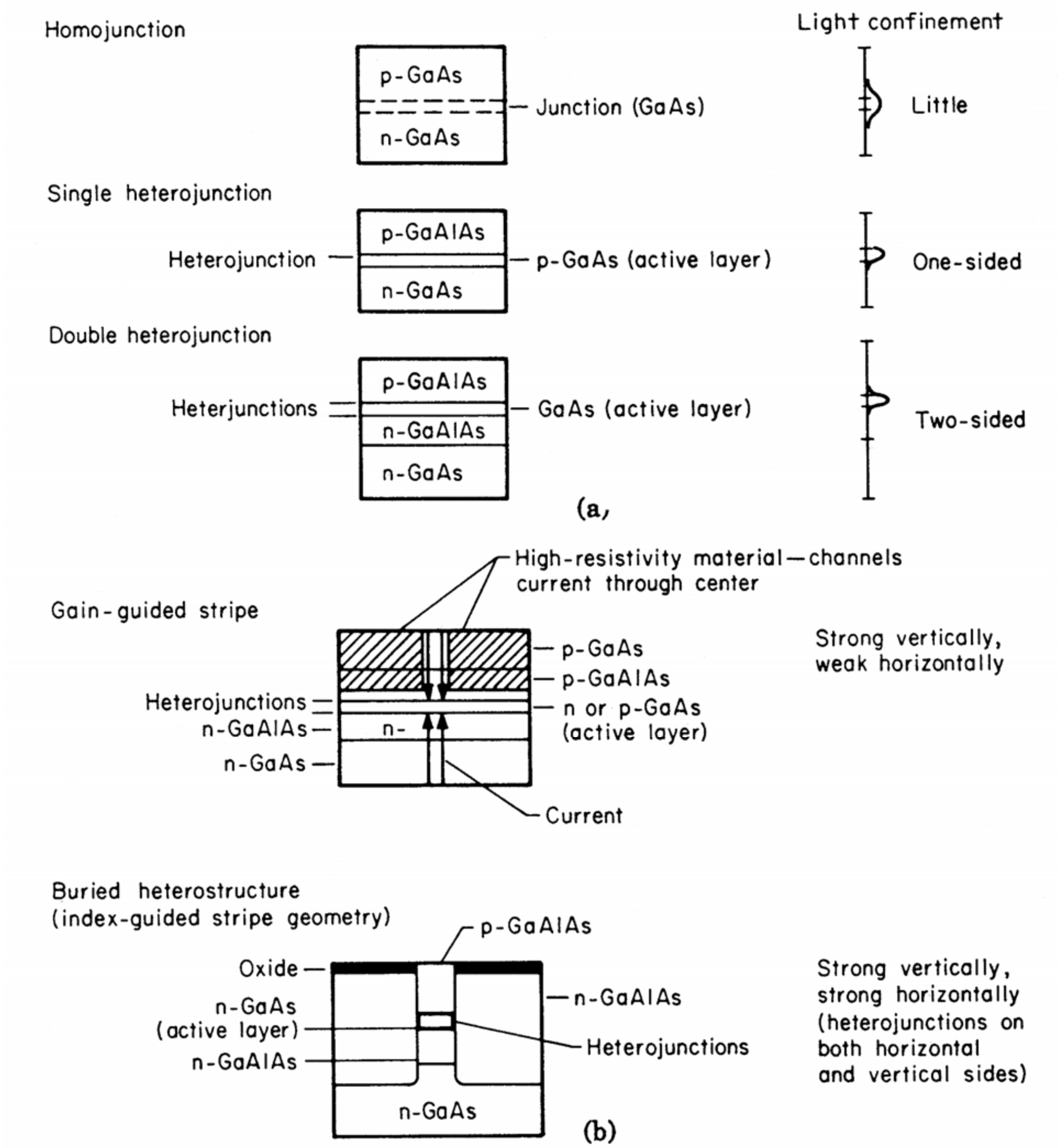


Figure 18.5 Major categories of edge-emitting diode lasers. (*a*) Three types shown in side views; (*b*) end views.

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

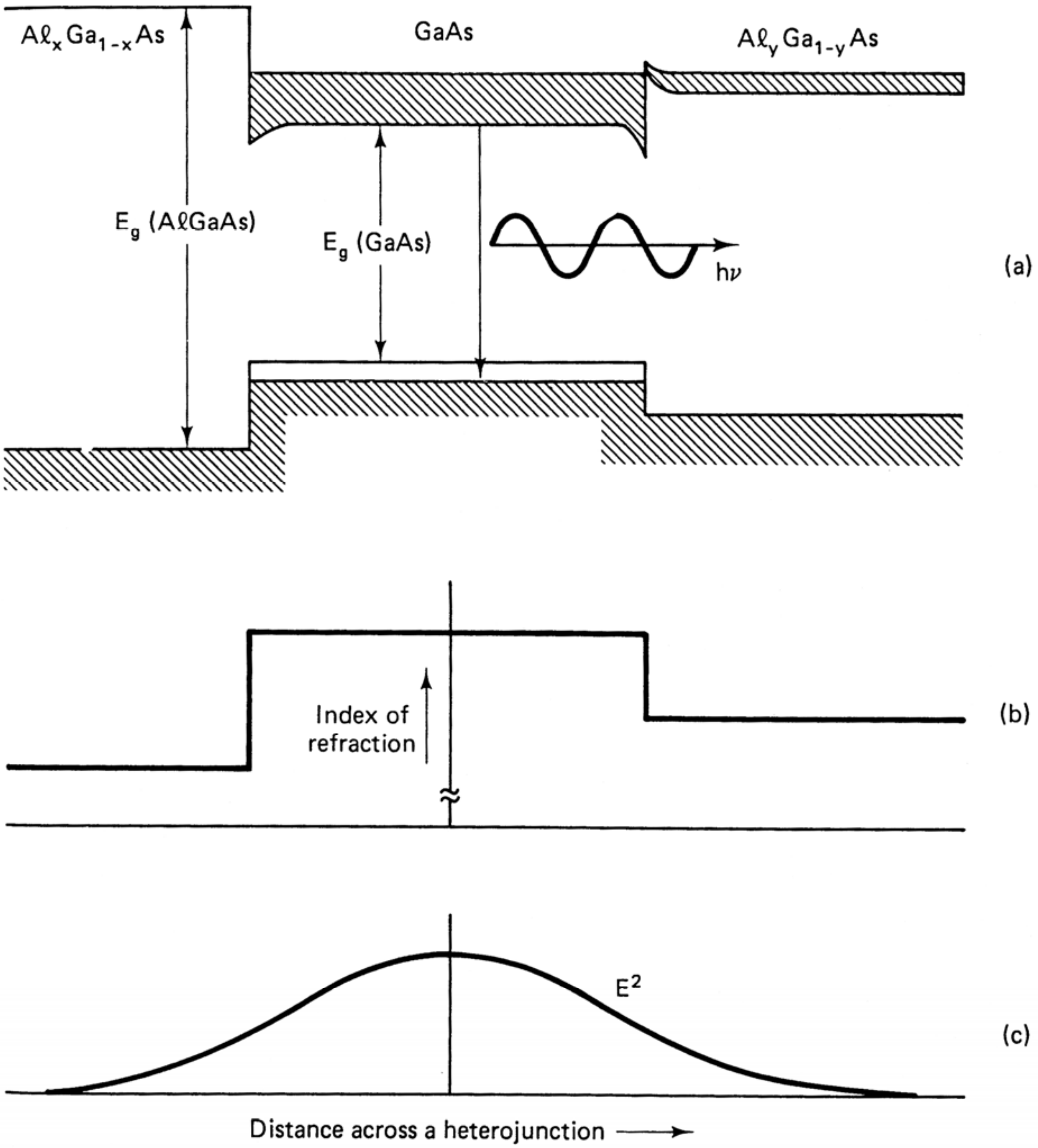


Figure 11.13 The band diagram for a forward-biased heterostructure in (a), the refractive index in (b), and a sketch of the light intensity in the vicinity of the active region in (c).

Comparison of Homo/Hetero/D-Heterojunctions Lasers

- As add index steps get smaller light spreading
- Single hetrojunction threshold current ~5x < homojunction
- Double hetrojunction threshold ~50-100x <homojunction
- Less current, less heating, more output before thermal limitations

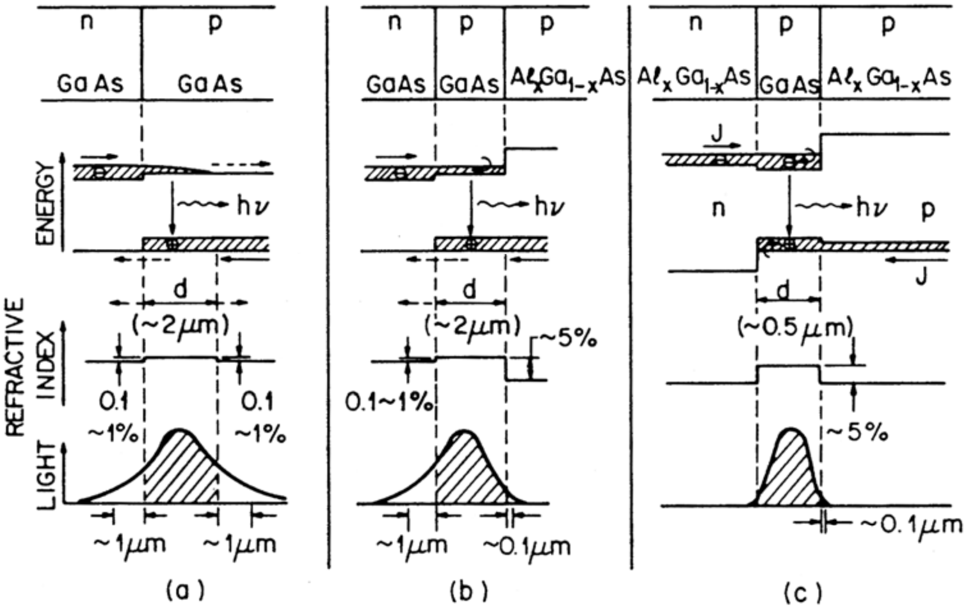


Fig. 27 Comparison of some characteristics of (*a*) homostructure, (*b*) single-heterostructure, and (*c*) double-heterostructure lasers. The top row shows energy-band diagrams under forward bias. The refractive index change for GaAs/$Al_xGa_{1-x}As$ is about 5%. The change across a homostructure is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

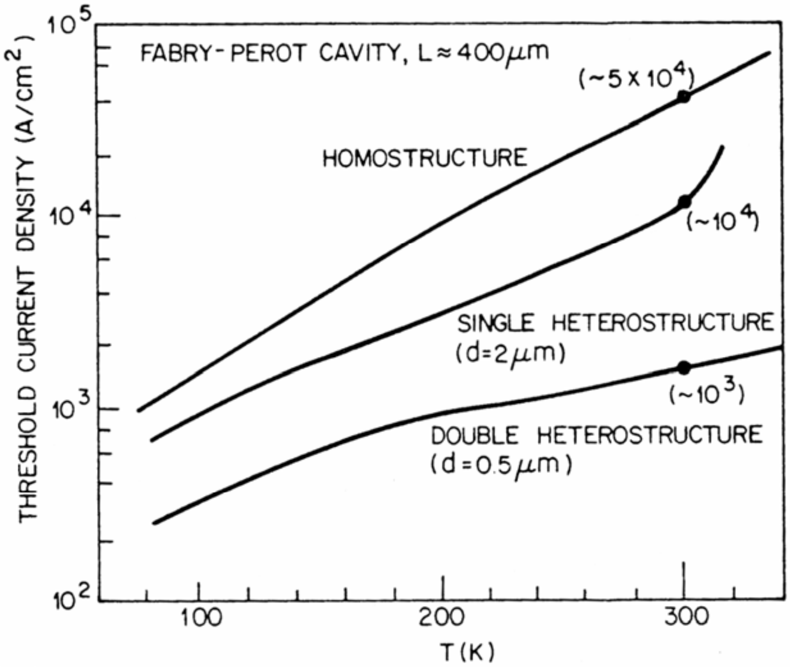


Fig. 28 Threshold current density versus temperature for three laser structures in Fig. 27. (After Panish, Hayashi, and Sumski, Ref. 48.)

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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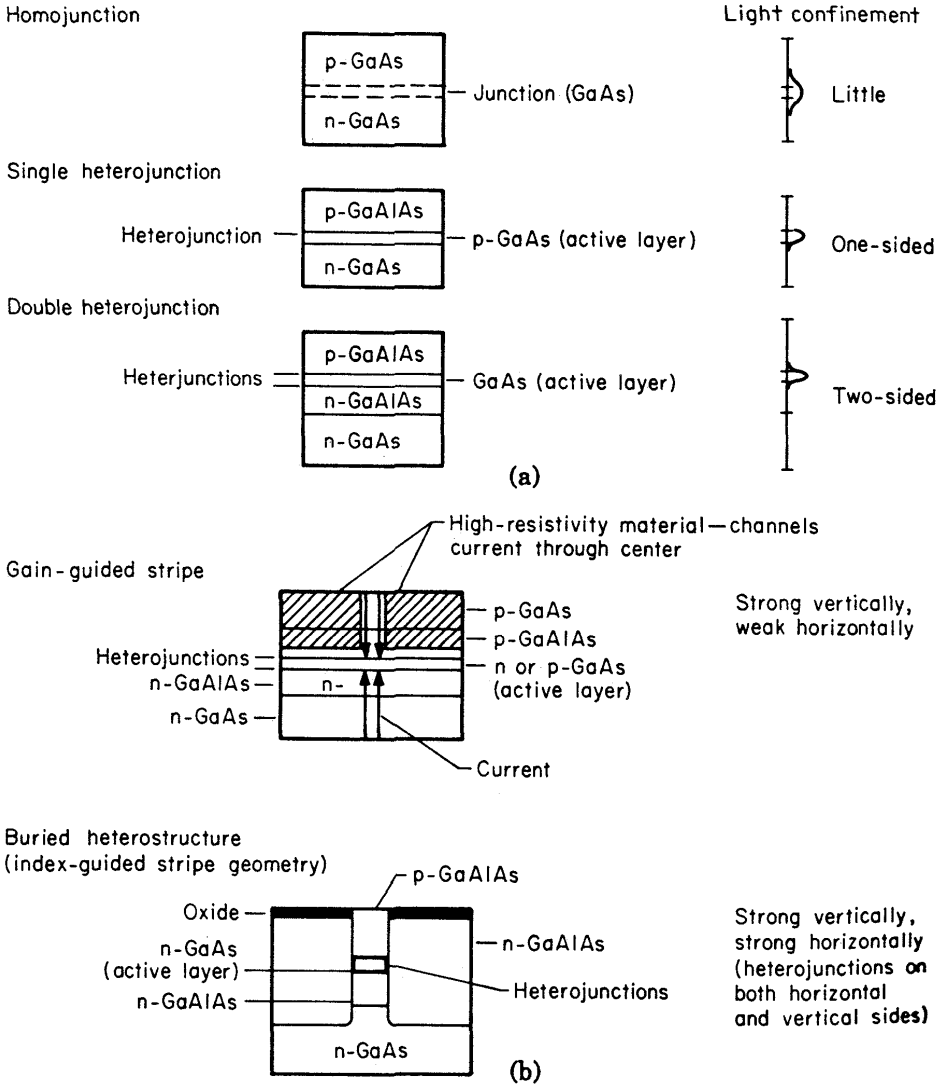


Figure 18.5 Major categories of edge-emitting diode lasers. (*a*) Three types shown in side views; (*b*) end views.

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

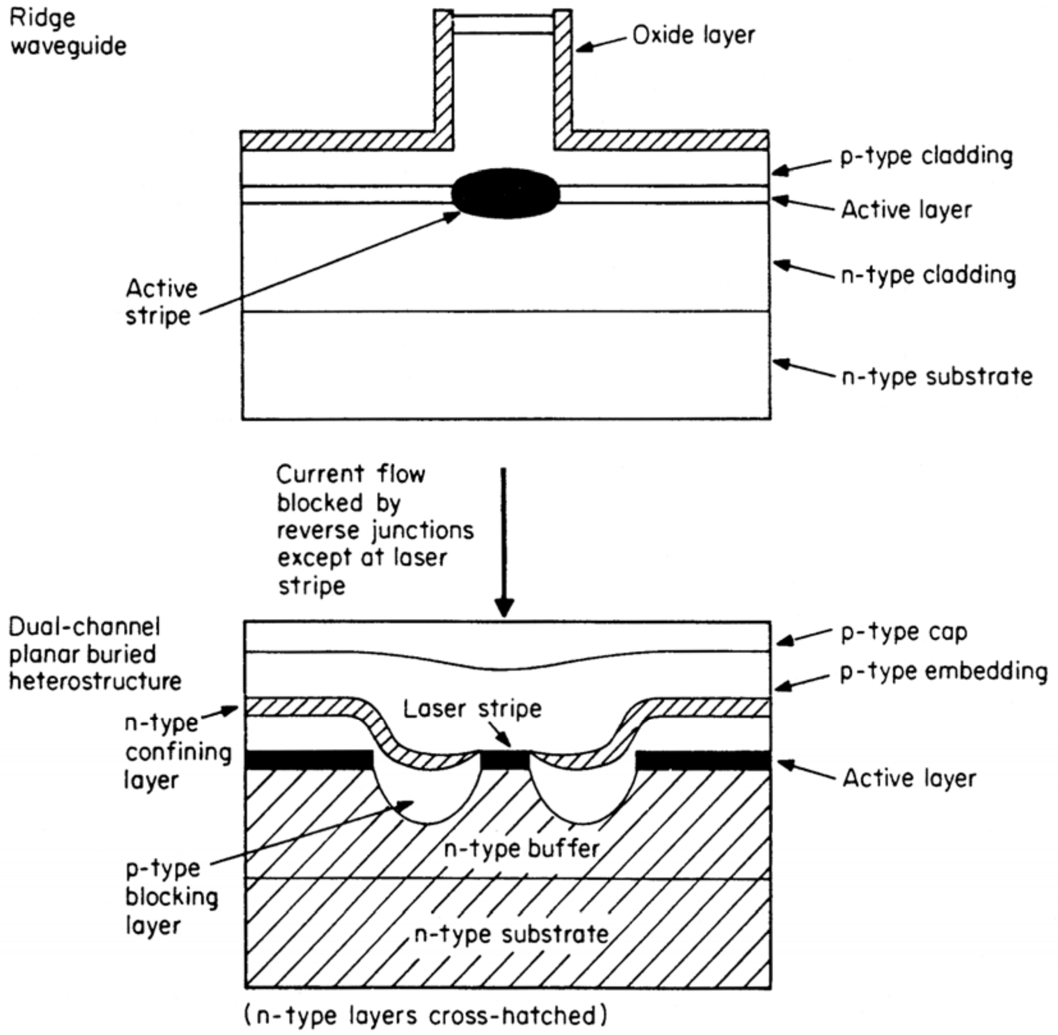


Figure 18.6 (*Continued*)

Quantum Well Materials

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

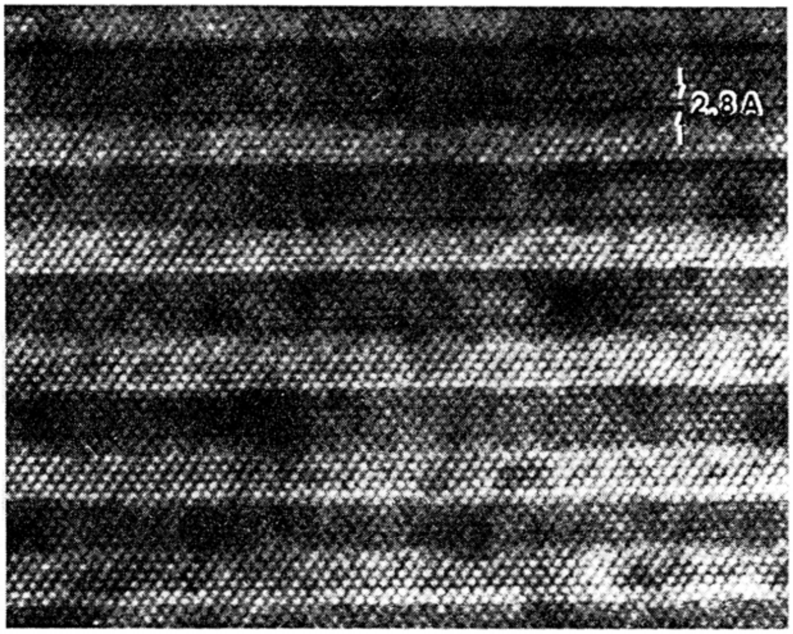
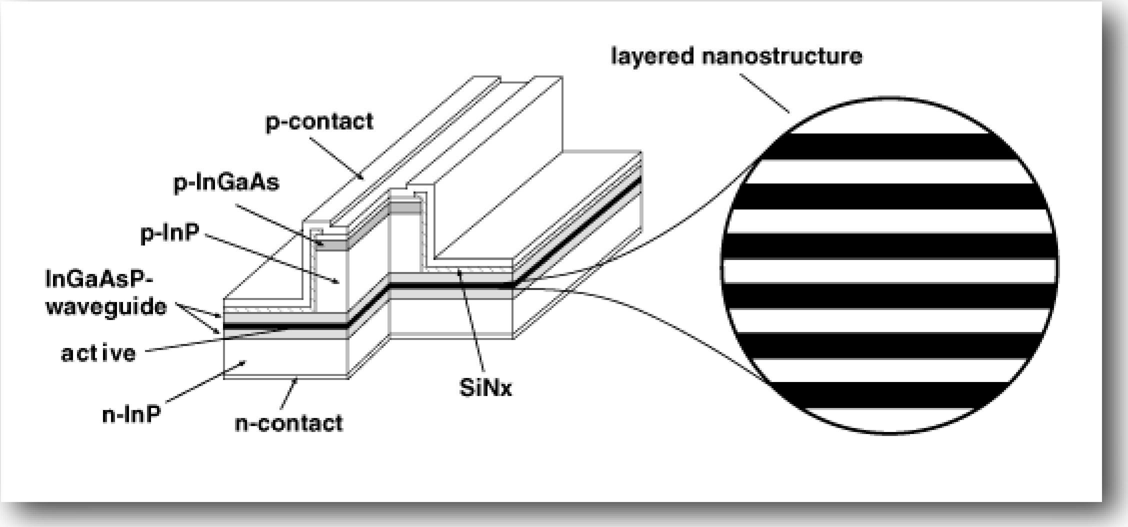


Figure 11.16 A multiple quantum well structure. This is a *t*ransmission *e*lectron *m*icroscope (TEM) display showing alternating layers of GaAs and $Al_xGa_{1-x}As$ materials. Note that the transition between the materials occurs abruptly on an atomic scale. (Data provided by Prof. J. J. Coleman.)



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

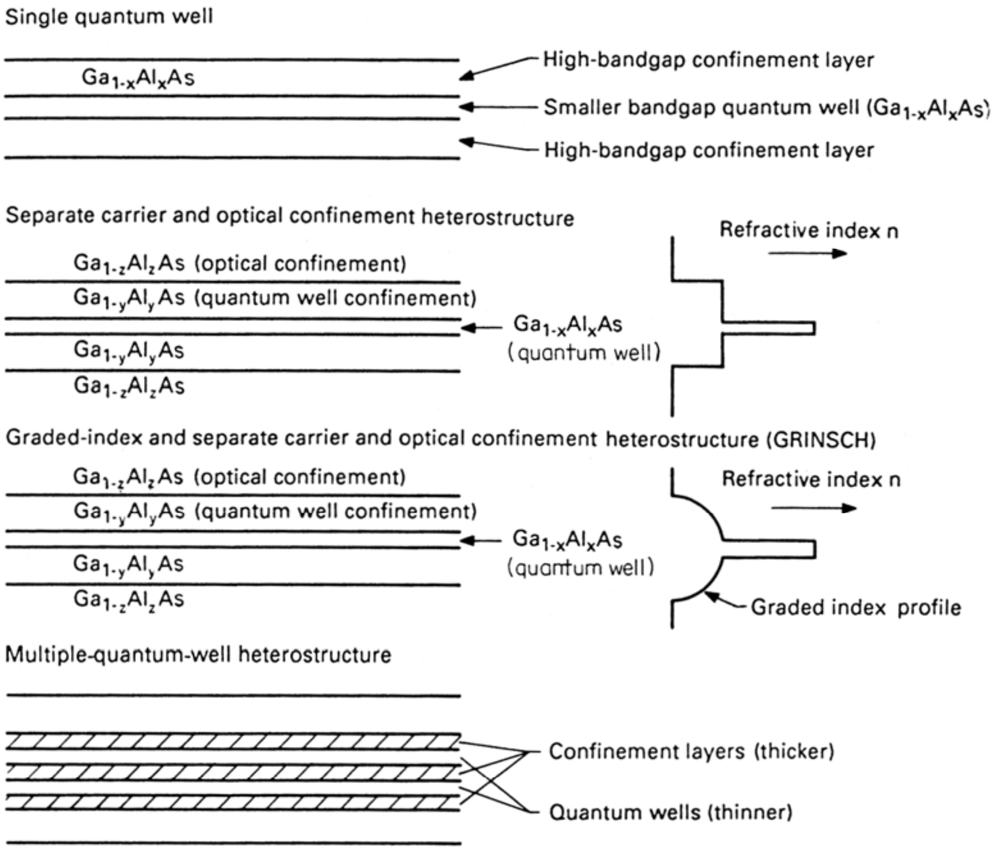
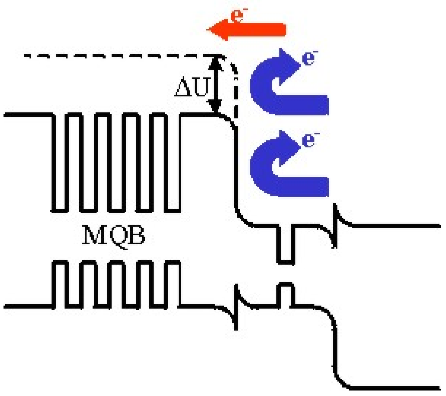


Figure 18.7 A single quantum well (top) is surrounded by thicker layers of higher-bandgap material. Forming layers with lower refractive index on top and bottom produces a separate carrier and optical confinement heterostructure (SCH). Grading the refractive index of the confinement layer produces the 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

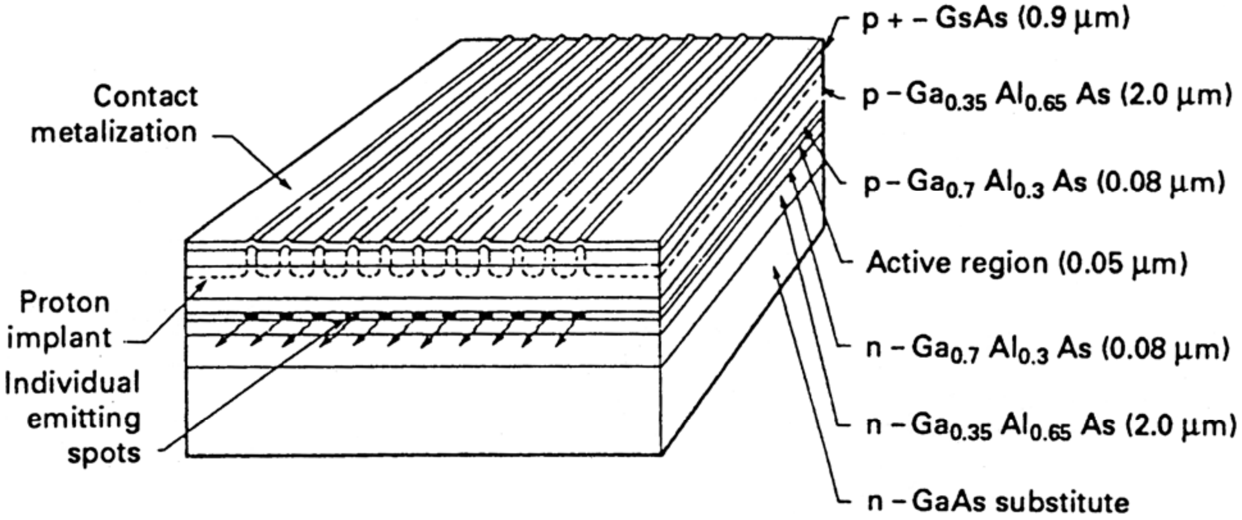


Figure 18.9 Monolithic array of diode laser stripes. (*Courtesy of Spectra Diode Laboratories.*)

Vertical Cavity Surface Lasers

- VCSL’s (Vertical Cavity Surface Lasers)
- Cavity built with doping
- Width a few microns
- Created 2 million lasers per sq. cm this way

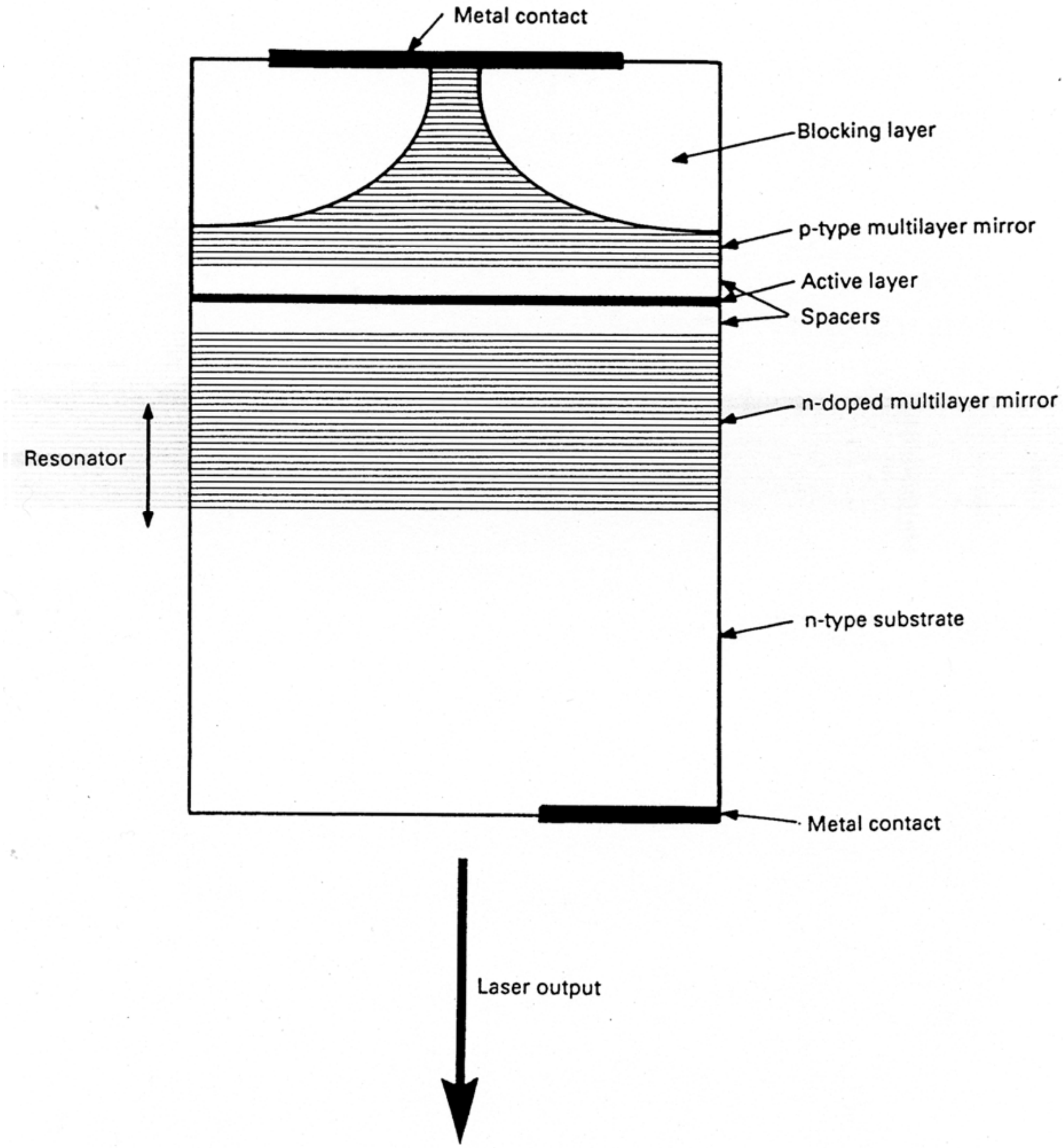


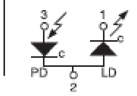
Figure 18.12 Vertical-cavity surface-emitting laser with mirrors above and below the active layer. In this version, the mirrors are multilayer structures fabricated as part of the diode structure; in other versions, one mirror may be a reflective metal or oxide film on the semiconductor surface.

Diode Laser Power & Control

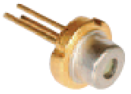
- Laser diodes are easily damaged
- As laser output increases, temperature rises, increases resistance
- Get thermal runaway
- Can permanently damage diode cleaved mirrors
- High power diodes have photodiode in same package
- Diode sees part of laser output, use feedback circuit to stabilize
- High power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

Pin Description

1	laser cathode
2	common case
3	monitor diode anode

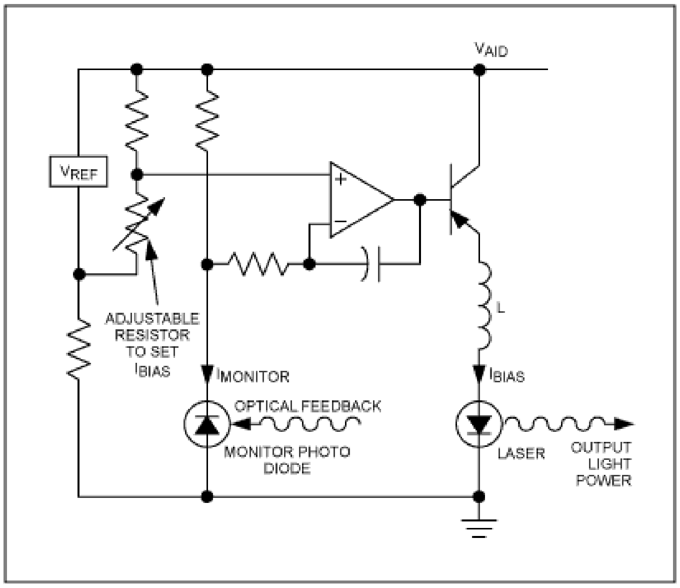


PIN CODE 5A



5.6mm PACKAGE

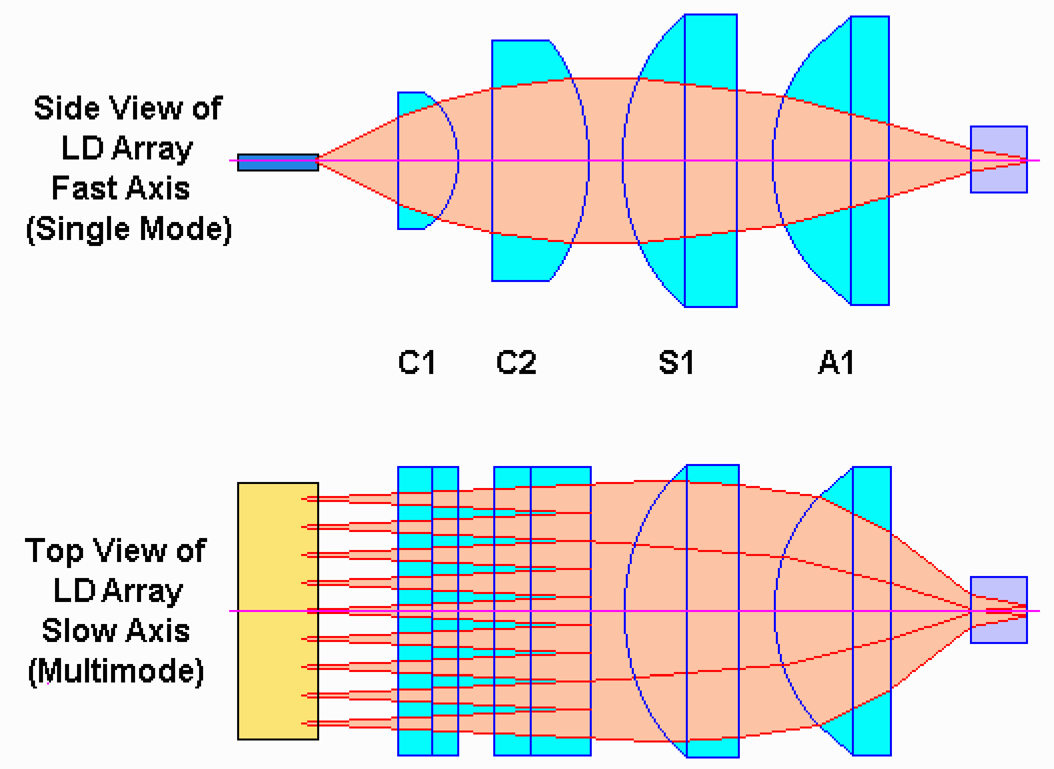
- 5.6mm Package
- AlGaInP Index-Guided MQW Structure
- 8µm Astigmatism @7mW
- High Operating Temperature 5mW at 60°C



TCLDM9

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

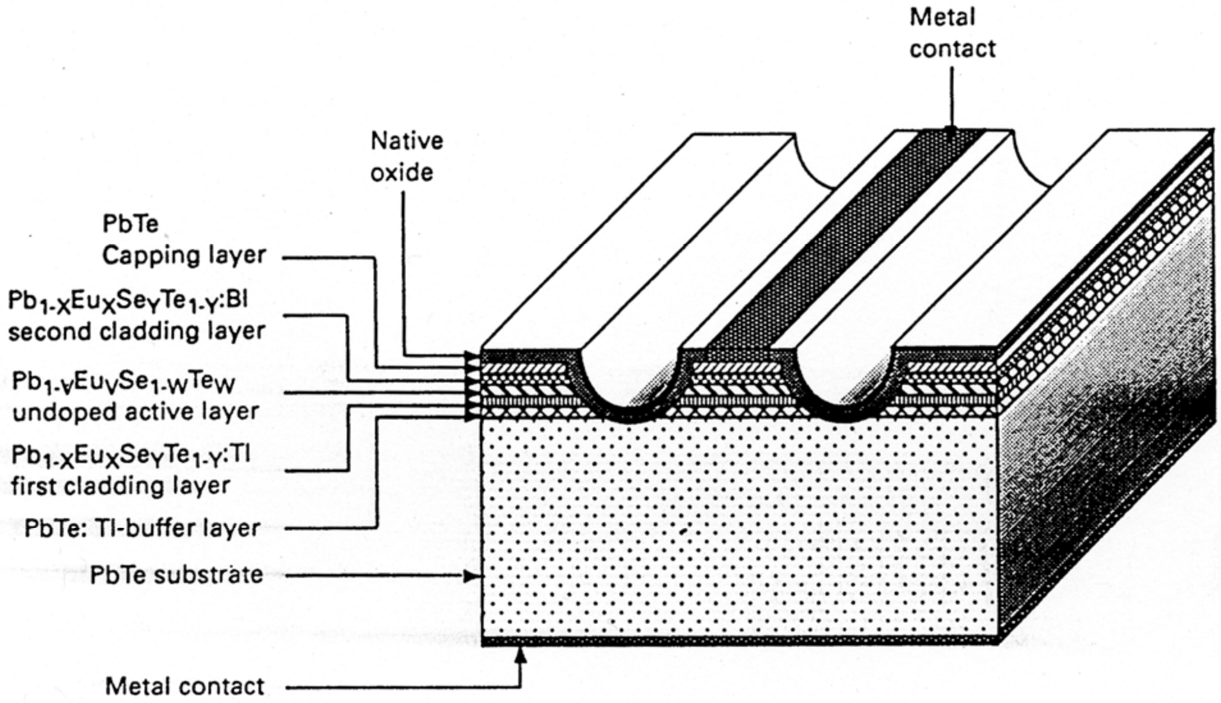


Figure 21.1 Double-channel PbEuSeTe laser with 20-μm mesa. (*Courtesy of Laser Photonics Inc.*)

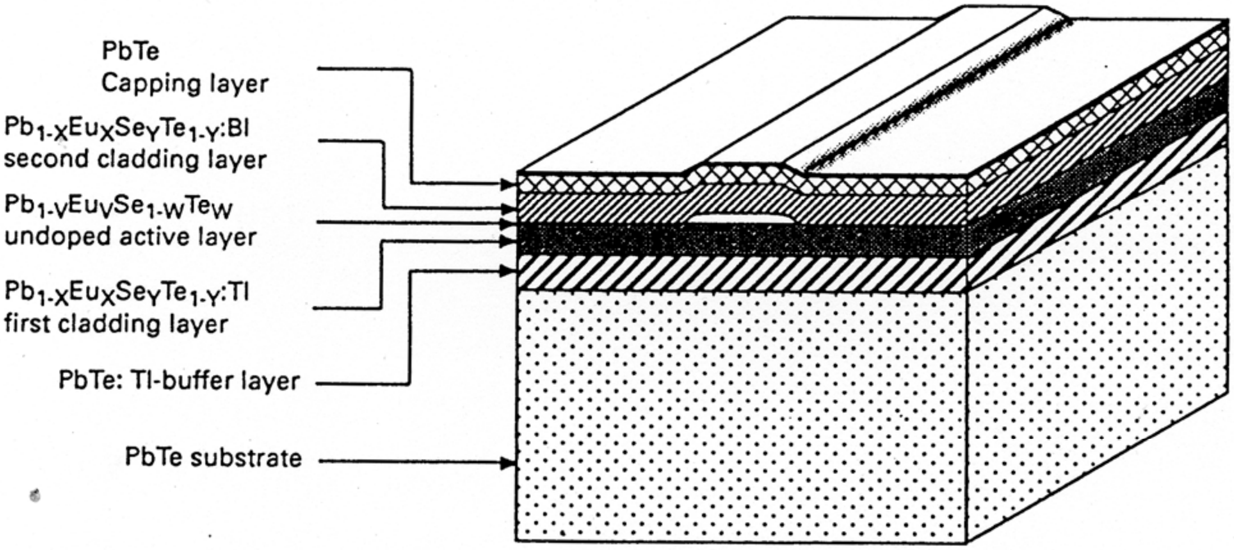


Figure 21.2 Buried-heterostructure PbEuSeTe laser with 4-μm stripe. (*Courtesy of Laser Photonics Inc.*)