13.8 Emission of Light

13.8.1 Spontaneous Emission

Luminescence: the emission of light due to reversion of electron from a higher energy state

- Photoluminescence is observed when **photons** impinge on a material which in turn re-emits light of a lower energy.

- **Electroluminescing** materials emit light **as a consequence of an applied voltage or electric field**.

- **Cathodoluminescence** is term which is used to describe light emission from a substance that has been showered **by electrons of higher energy**

- **Thermoluminescence** Spontaneous light emission occurs also in common devices such as candles or incandescent light bulbs. In both of these cases, the electrons have been excited into higher energy states **by heat energy**.

Fluorescence: the electron transition occurs within nanoseconds or faster

Phosphorescence: the emission takes place after microseconds or milliseconds (slower process)

Afterglow: even slower (seconds), occurs when excited electrons have been temporarily trapped in impurity states from which they eventually return after some time into the valence band

Laser: light amplification by stimulated emission of radiation

13.8.2 Stimulated Emission (Lasers)

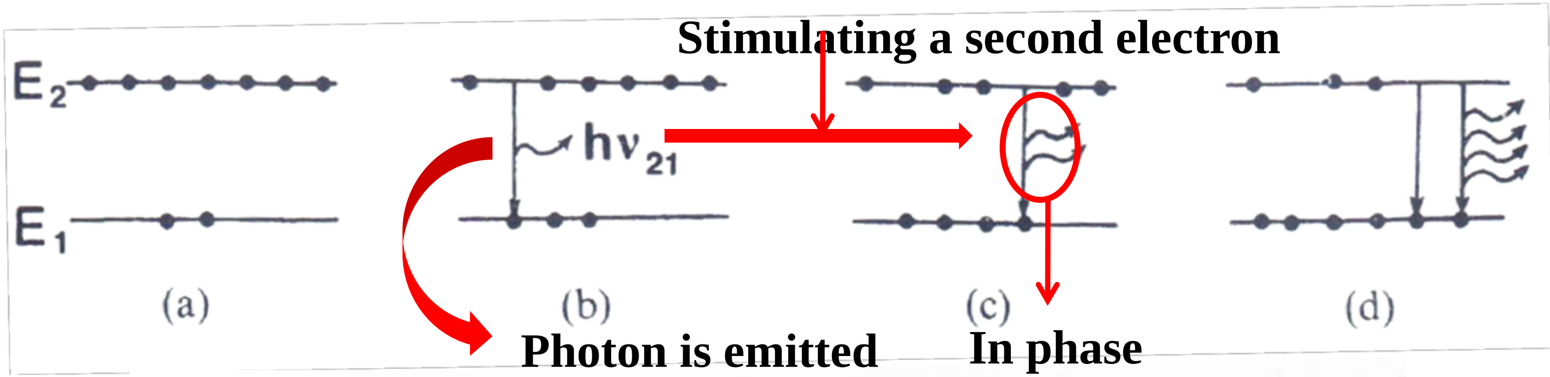


Figure 13.32. Schematic representation of stimulated emission between two energy levels, E_2 and E_1. The dots symbolize electrons.

Light amplification by stimulated emission of radiation with monochromatic wave

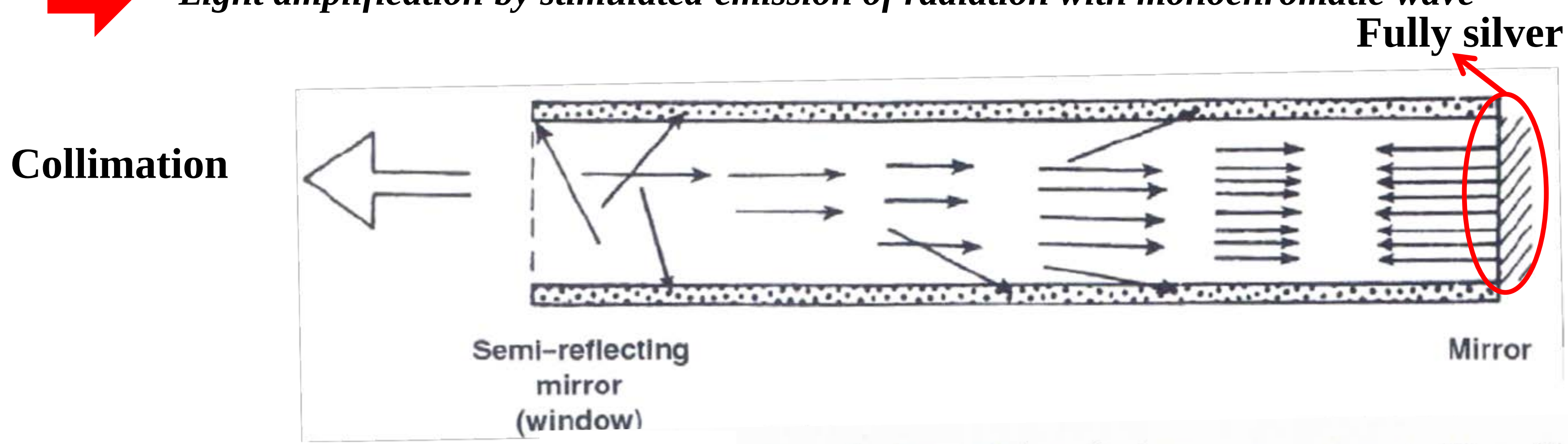


Figure 13.33. Schematic representation of a laser cavity and the buildup of laser oscillations. The stimulated emission eventually dominates over the spontaneous emission. The light leaves the cavity at the left side.

13.8 Emission of Light

Optical pumping

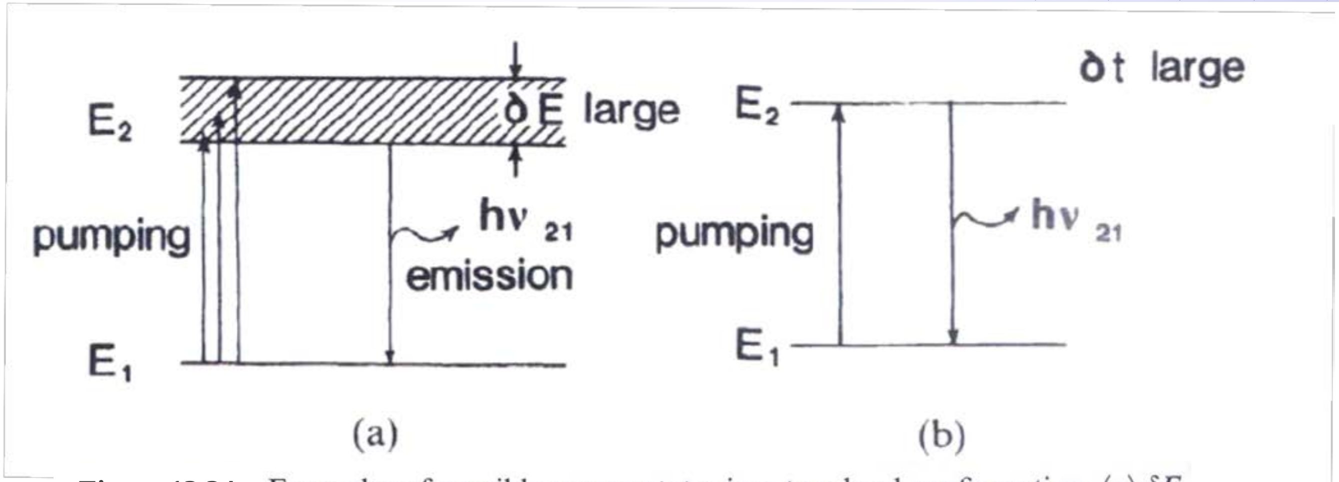


Figure 13.34. Examples of possible energy states in a two-level configuration. (a) δE large, i.e., large pumping efficiency but little or no population inversion. (b) Potentially large population inversion (δt large) but small pumping efficiency. (*Note:* Two-level lasers do not produce a population inversion, because absorption and emission compensate each other.)

Pumping efficiency is large if the band width of the upper electron state is broad

$$\delta E \cdot \delta t \propto h$$ **Heisenberg's uncertainty principle**

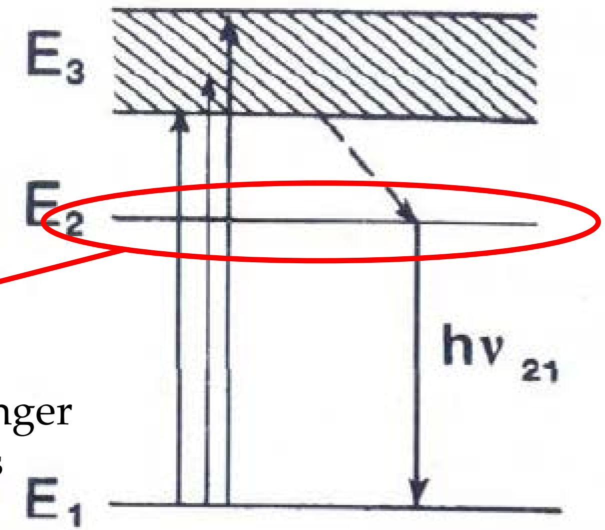
The time span which an electron remains at the higher energy level

Population inversion

13.8 Emission of Light

Three-level laser

Broad pump band E3 enables a good pumping efficiency



Intermediate lever
- The electrons remain much longer
- Population inversion increases

Figure 13.35. Three-level laser. The nonradiative, phonon-assisted decay is marked by a dashed line. Lasing occurs between levels E_2 and E_1. High pumping efficiency to E_3. High population inversion at E_2.

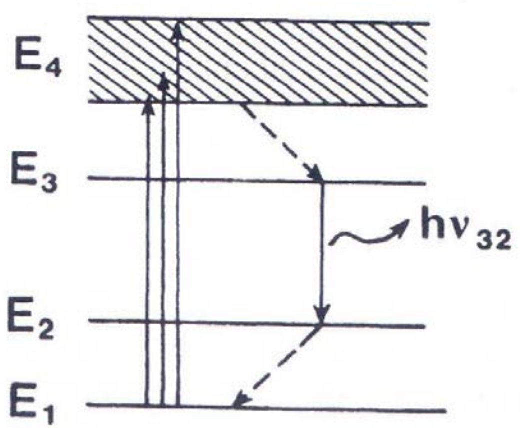


Figure 13.35. Four-level laser.

Four-level laser

- The energy level E_2 is emptied rapidly by electron transitions into a lower level, E_1

13.8.3 Helium-Neon Laser

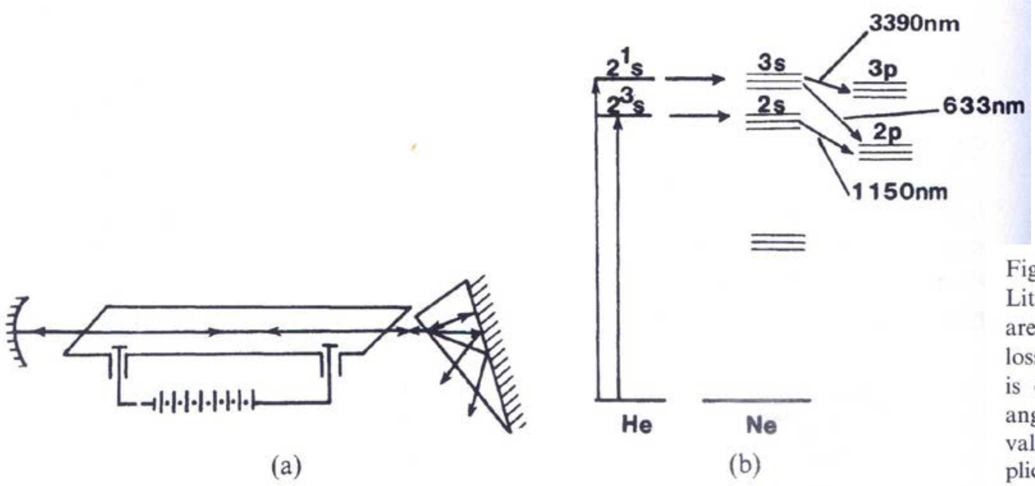


Figure 13.36. Helium–neon laser. (a) Schematic diagram of the laser cavity with Littrow prism to obtain preferred oscillation at one wavelength. (The end windows are inclined at the Brewster angle for which plane-polarized light suffers no reflection losses.) (b) Energy level diagram for helium and neon. The decay time for the *p*-states is ~10 ns; that of the *s*-states 100 ns. The letters on the energy levels represent the angular momentum quantum number; the number in front of the letters gives the value for the principal quantum number; and the superscripts represent the multiplicity (singlet, doublet, etc.), see Appendix 3.

13.8.4 Carbon Dioxide Laser

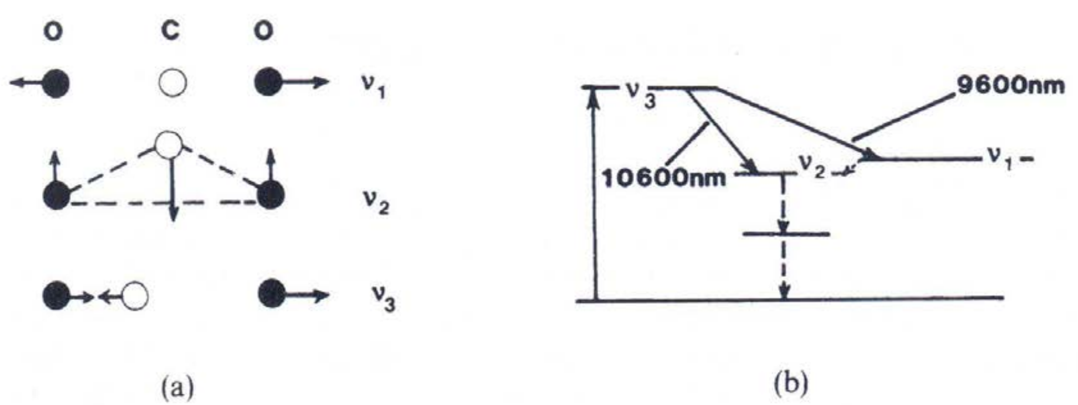


Figure 13.37. CO_2 laser. (a) Fundamental modes of vibration for a CO_2 molecule; ν_1: symmetric stretching mode; ν_2: bending mode; ν_3: asymmetric stretching mode. (b) Energy level diagram for various vibrational modes.

13.8.5 Semiconductor Laser

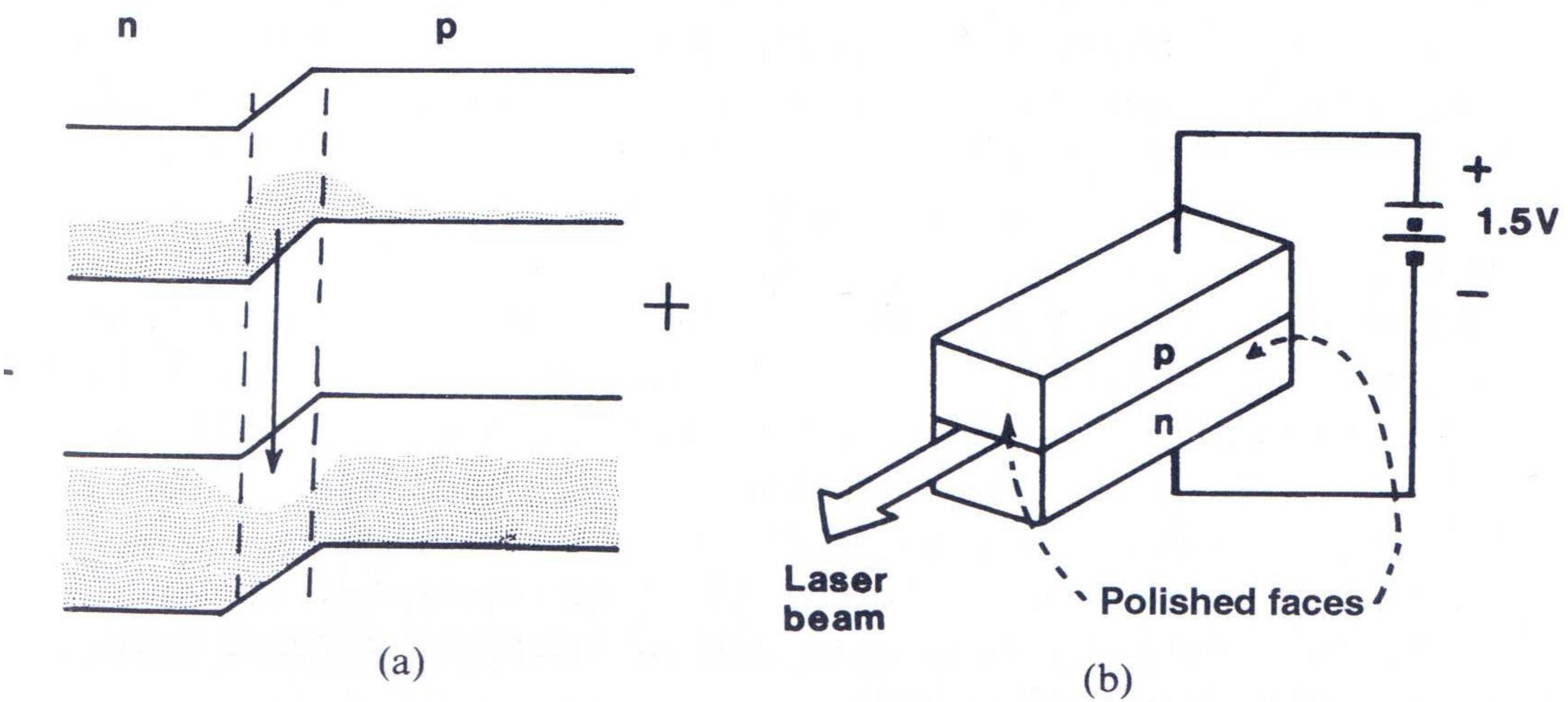


Figure 13.38. (a) Energy band diagram of a heavily doped, forward-biased semiconductor. (b) Schematic setup of a semiconductor laser.

13.8.6 Direct-Versus Indirect- Band Gap Semiconductor Lasers

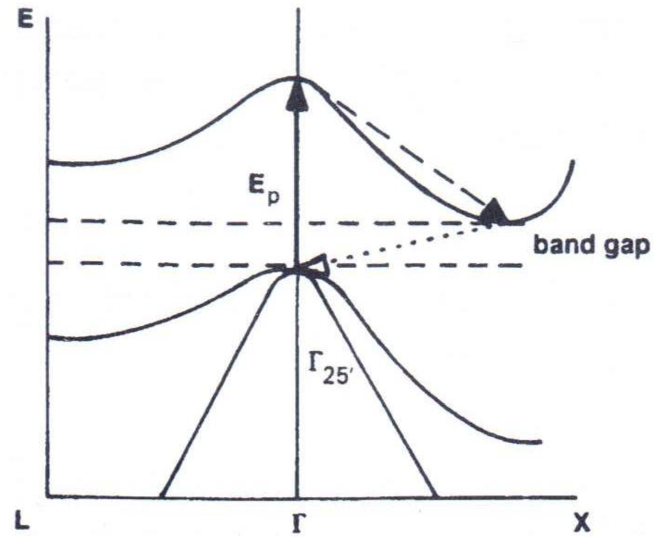


Figure 13.39. Direct interband transition pumping (E_p) and phonon-involved reversion of a *hot* electron by indirect transitions for an indirect–band gap semiconductor such as silicon. (Compare with Figs. 5.23 and 12.2.)

Indirect-band gap semiconductors (phonon-assisted process involved) seem to be not suited for lasers.

13.8 Emission of Light

13.8.7 Wavelength of Emitted Light

- The band gap, i.e., the wavelength at which a laser emits light, can be adjusted to a certain degree by utilizing ternary or quaternary compound semiconductors

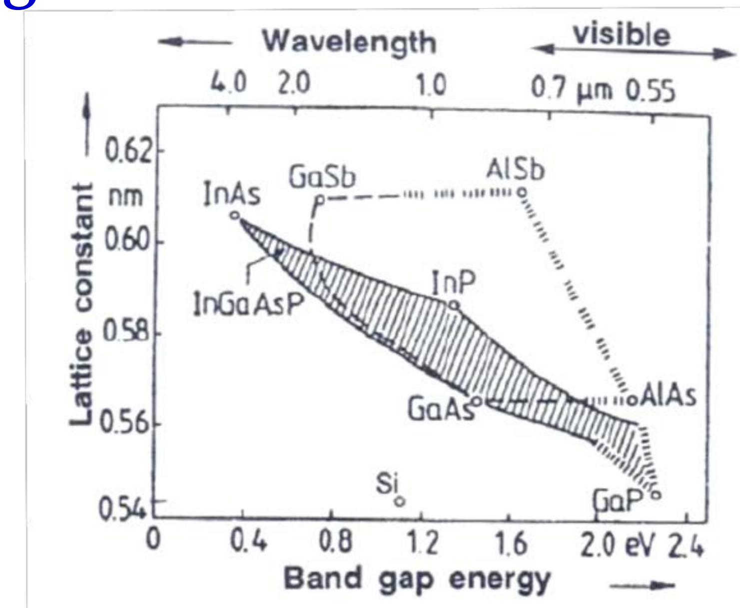


Figure 13.40. Lattice constants, energy gaps, and emission wavelengths of some ternary and quaternary compound semiconductors at 300 K. The lines between the binary compounds denote ternaries. The cross-hatched lines indicate indirect interband transitions. Pure silicon is also added for comparison.

$$E_{gT} = E_{g0} - \frac{\xi T^2}{T + \theta_D}$$

- The emission wavelength depends on the temperature of operation, because the band gap decrease with increasing temperature according to the empirical equation

13.8.8 Threshold Current Density

13.8.9 Homojunction Versus Heterojunction Lasers

13.8.10 Laser Modulation

For telecommunication purposes it is necessary to impress an AC signal on the output of a laser to modulate directly the emerging light by the speech. This can be accomplished by **amplitude modulation** by biasing the laser initially above the threshold and then superimposing on this DC. Another possibility is **pulse modulation** the generation of sub-nanosecond pulses having nanosecond spacing between them.

Frequency modulation can be achieved by applying perpendicularly to the diode junction, a periodic varying mechanical pressure, thus periodically altering the dielectric constant of the cavity.

13.8.11 Laser Amplifier

13.8.12 Quantum Well Lasers

- The carriers are confined to a potential well having infinitely high walls.

- The light emission in a quantum well laser occurs as a result of electron transitions from these conduction band levels into valence levels.

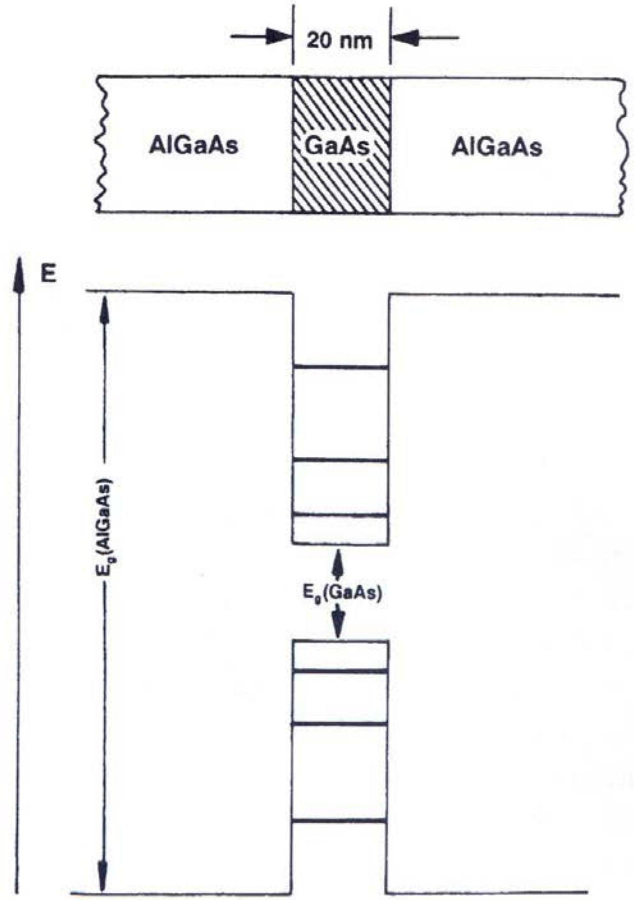


Figure 13.45. Band structure of a single quantum dot structure. See in this context Section 8.7.10 and Fig. 8.33(b).

13.8.13 Light-Emitting Diodes (LED)

-The LED consists, like semiconductor laser, of a forward biased *p-n* junction

- The light emission occurs in the visible spectrum

- III-V compound semiconductor, such as $Ga_xAs_{1-x}P$, GaP, $Ga_xAl_{1-x}As$ (for red and yellow-green), nitride-based compound semiconductors (for green and blue colors)

- **Chromaticity diagram** : It is based on the peculiarities of the three types of cones in the human eyes which are sensitive for either blue, green, or red radiation

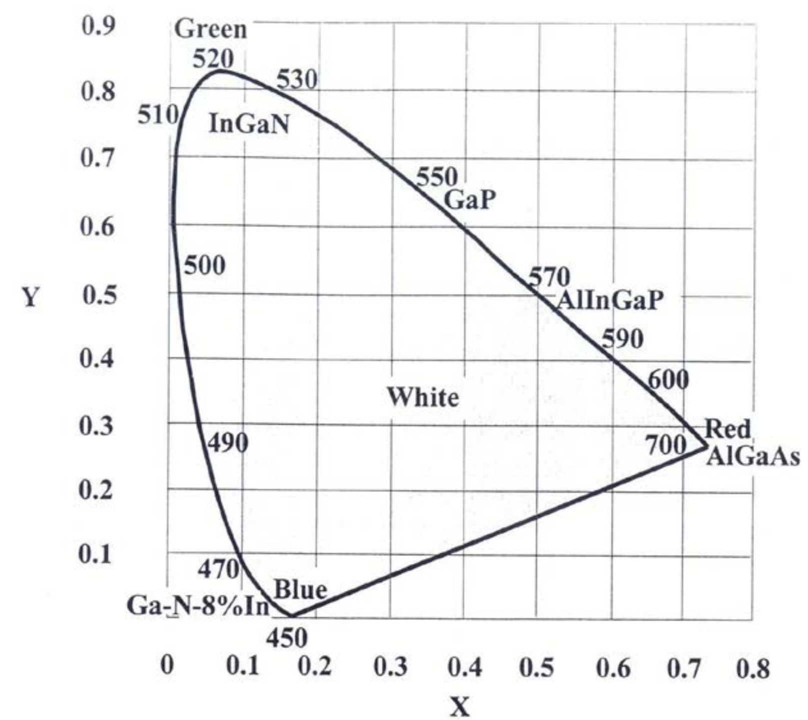


Figure 13.46. Chromaticity diagram in which the positions of some commercially available LEDs are shown.

13.8.14 Organic Light Emitting Diodes (OLEDs)

- Organic light emitting diodes work in principal quite similar to inorganic LEDs like GaAsP or GaN diodes.

- Electrons and holes are injected from opposite sides into suitable organic materials where they combine to form electron/hole pairs and relax to the ground state by emitting photons.

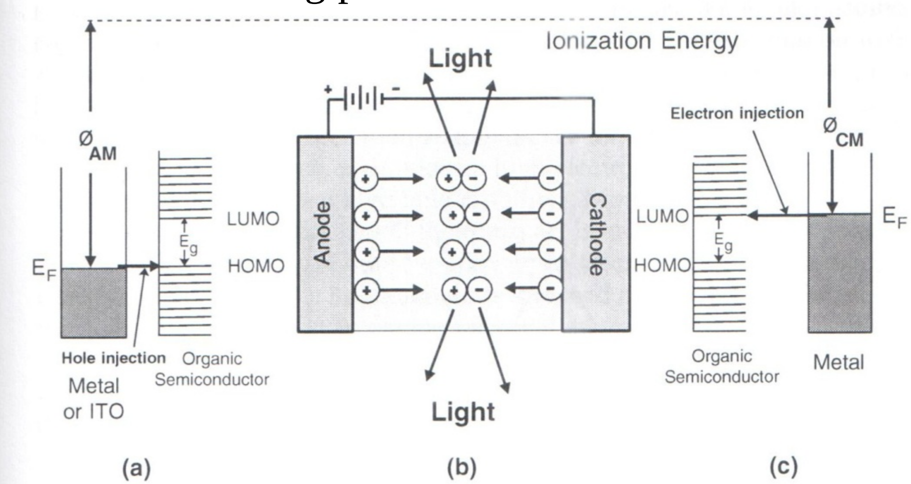


Figure 13.47. Schematic representation of a **single-layer organic light emitting diode**. (a) A metal "band diagram" adjacent to HOMO/LUMO levels of an organic semiconductor is depicted. Hole injection is indicated. (b) Schematic functioning of a single layer OLED. (c) HOMO/LUMO levels and metal "band diagram" for electron injection. HOMO = highest occupied molecular orbital; LUMO = lowest unoccupied molecular orbital, see page 186. $Ø_{AM}$ = Work function for an anode metal. $Ø_{CM}$ = Work function of a cathode metal; E_g = band gap energy, E_F = Fermi energy.

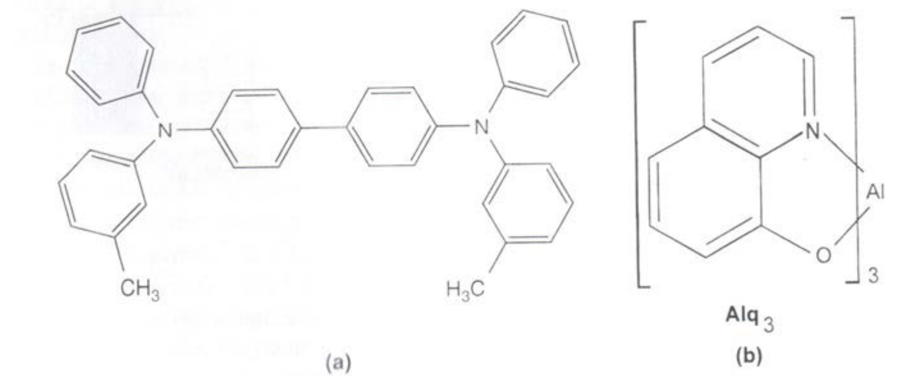


Figure 13.48. Chemical compounds for OLEDs. (a) N,N',-diphenyl-N,N'-bis(3-methylphenyl)-(1,1'-biphenyl)-4,4'-diamine (TPD) (b) Alq_3 also known as tris(8-hydroxyquinoline) aluminum having the formula $Al(C_9H_6NO)_3$.

13.8.15 Organic Photovoltaic Cells(OPVCs)

- The principal design of an organic solar cell is quite similar to the OLED in Fig. 13.47.

- The battery is replaced by a voltmeter or the load. The direction of light is reversed.

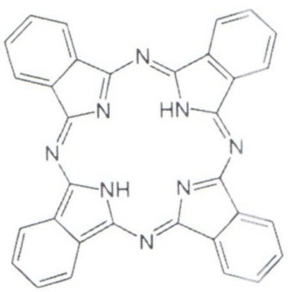


Figure 13.50. Example of a conjugated organic molecule (phthalocyanine) used for organic photovoltaic devices.

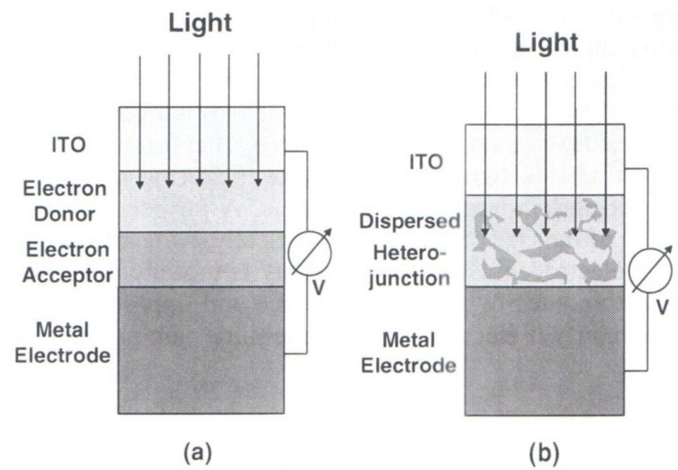


Figure 13.51. Schematic representations of (a) a multilayer organic photovoltaic cell; (b) a dispersed heterojunction OPVC.

13.8.16 Liquid Crystal Displays (LCDs)

- LCD s contain peculiar viscous liquids whose rod-shaped molecules are arranged in a specifically ordered pattern : Each of these rod-shaped molecules has a strong electric dipole moment and can be oriented in a glass container and is initially treated so that the molecules on one end are aligned at right angles to the ones on the other end (Fig13.52a)

- If a small voltage is applied to the conducting end faces of the liquid crystal, the molecules align parallel to the field direction and the light is therefore not caused to change its polarization (fig 13.52b)

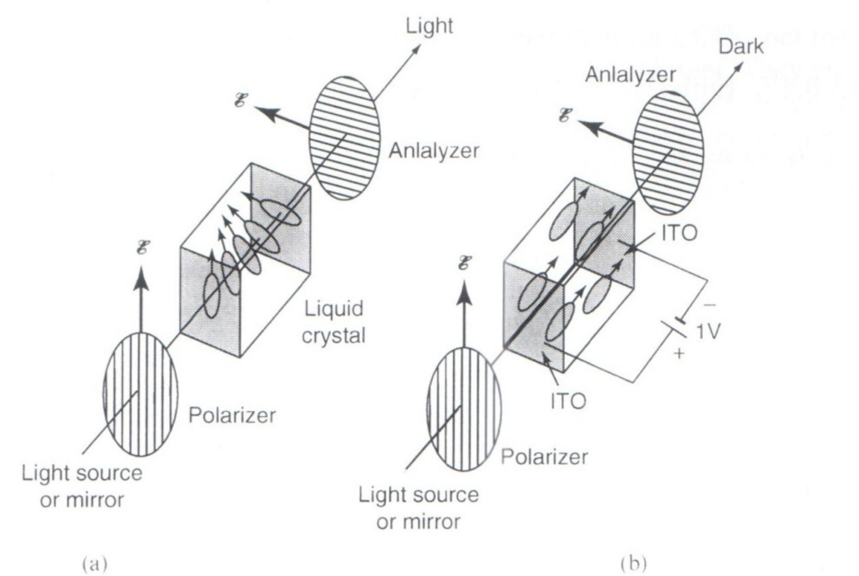


Figure 13.52. Schematic representation of a liquid crystal display unit (a) in the light-transmitting mode, (b) in the non-light-transmitting mode, caused by a potential that is applied to the end faces of the (twisted nematic) liquid crystal. Polarizer and analyzer are identical devices that allow the light (i.e., the electric field vector) to oscillate in only one direction as indicated by arrows (see also Section 13.1.2). The end faces of the liquid crystal–containing glass vessel are coated by transparent electrodes such as indium-tin-oxide (ITO), see Section 9.3.

13.8.17 Emissive Flat-Panel Displays

Electroluminescent devices utilize a thin phosphor film, such as manganese-doped zinc sulfide, which is sandwiched between two insulating films. The light emission is generally induced by an alternating electrical potential applied between the two conducting electrodes. This generates an electric field amounting to about 10^6 V/m across the phosphor layer, which causes an injection of electrons into the phosphor. Once the threshold voltage has been exceeded, the electrons become ballistic and excite the electrons of the activator atom in the phosphor into a higher energy state. Upon reverting back into the ground state, photons of the respective wavelength are generated

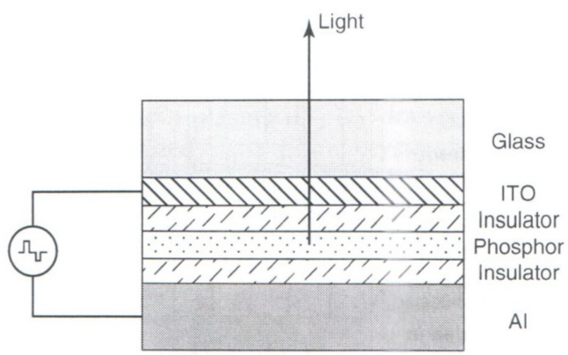


Figure 13.53. Schematic diagram of an electroluminescent device operated by alternating current pulses of about 200 V. The thin-film layers are about 300 nm thick except in the case of the phosphor, whose thickness is between 600 and 1,000 nm. The phosphor consists of the host matrix, such as a wide-band gap metal sulfide (ZnS, CuS, SrS), and an "activator", also called "luminescence center", such as Mn, Tb, Eu, Ce, Sm, Cu, Ag, etc.

13.8.17 Emissive Flat-Panel Displays

Plasma display devices operate quite similar to fluorescence light bulbs. A relatively high AC voltage is applied across a discharge gas to create a plasma. Recombination of electron-ion pairs in the plasma causes photons of high energy. They are absorbed by the phosphors which in turn emit visible light.

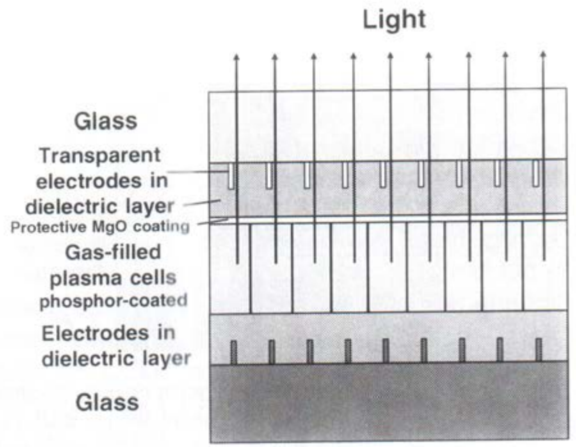


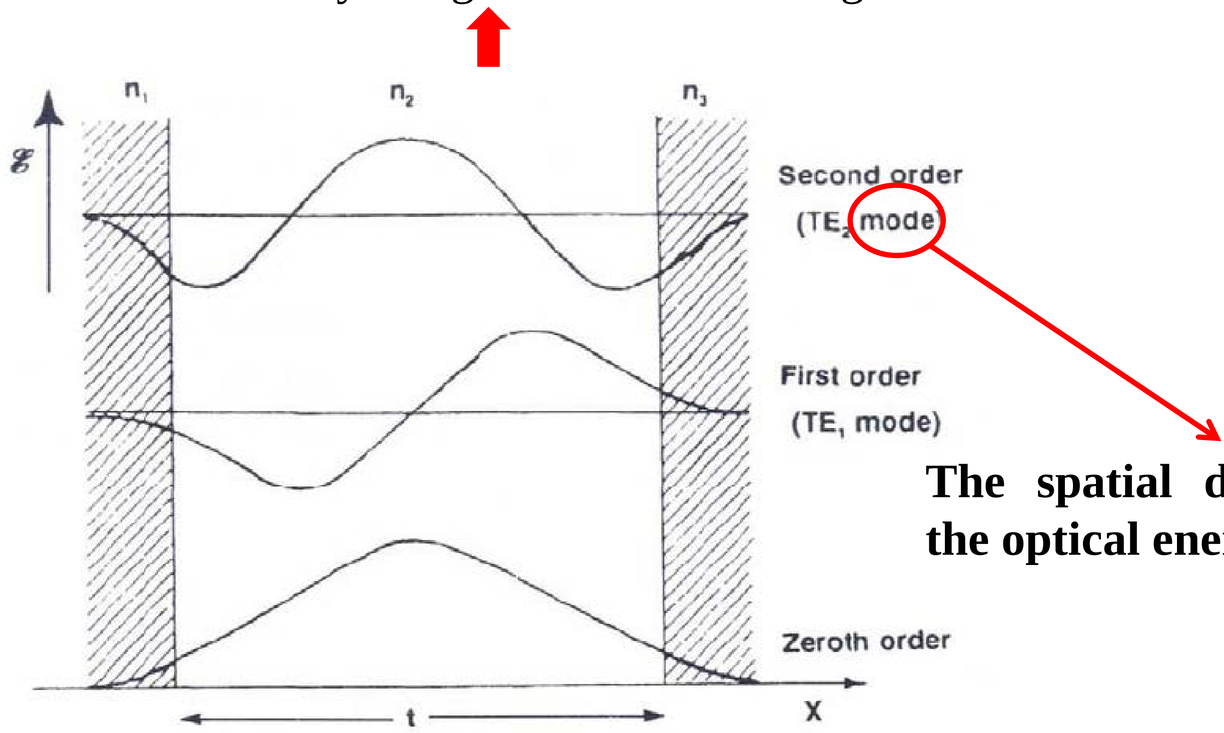
Figure 13.54. Schematic representation of a plasma display (not drawn to scale).

Field-emission displays are still in the experimental stage. The aim is to build them flat with wide viewing angles and fast response times. They consist of a large number of tip-shaped field-emitters that can be matrix-addressed and which emit, when hermetically encapsulated into a vacuum, substantial amounts of electrons under the influence of high electric fields. These electrons impinge on phosphors of various kinds to cause cathodoluminescence in different colors

13.9.1 Passive Waveguides

- **waveguide** : The interconnecting medium between various optical devices

Reflectivity is lager than other 2 things



The spatial distribution of the optical energy

Figure 13.55. Electric field strength distribution (modes) in a waveguide assuming $n_1 = n_3$ (symmetric behavior). The zeroth order and higher-order modes are shown. (Compare with Fig. 4.8.)

13.9.2 Electro-Optical Waveguides (EOW)

-Schottky-barrier contact which, when reverse biased, forms a wide depletion layer

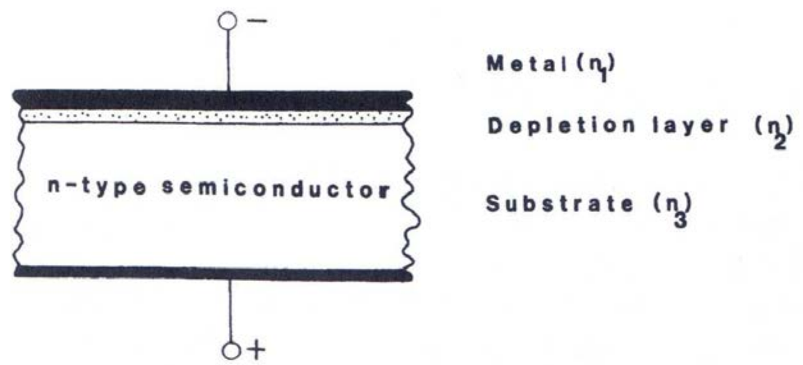


Figure 13.56. Electro-optical waveguide making use of a reverse-biased Schottky-barrier contact. (See also Fig. 8.15.) The light travels in Medium 2 (the depletion layer) when a high-enough voltage is applied to the device.

$$n_2 - n_3 = \frac{e^2 \lambda^2}{2n_3 4\pi^2 \varepsilon_0 m^* c^2}(N_{f3} - N_{f2})$$

For the device to become optical waveguide, the doping of the substrate needs to be reasonably high in order that an appreciable change in the index of refraction is achieved.

13.10 Optical Storage Devices

-The most common application, the compact disk (CD), is a *random-access*, *read-only* memory device

- The information is stored below a transparent, polymeric medium in the form of bumps, as shown in Fig 13.55

-The CD is read from the back side, i.e., the information is now contained in the form of bumps.

- The aligning of the laser beam on the extremely narrow tracks : three light beam, obtained by dividing into three parts the impinging laser beam shown in Fig. 13.55b utilizing a grating or holographic element

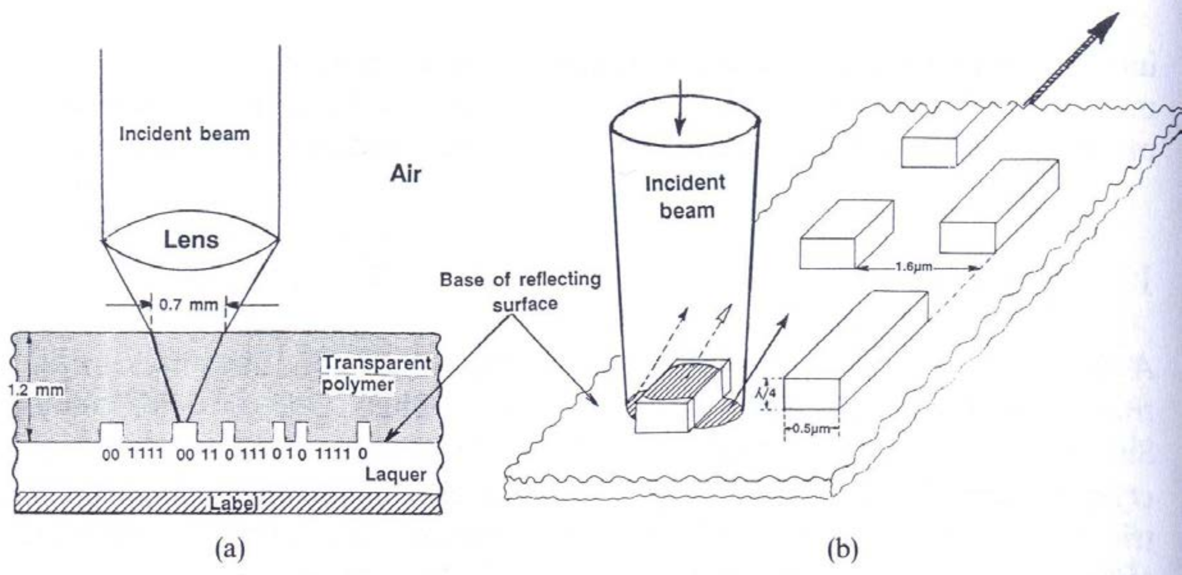


Figure 13.61. Schematic of a compact disk optical storage device. Readout mode. (Not drawn to scale.) The reflected beams in Fig. 13.55(b) are drawn under an angle for clarity. The land and bump areas covered by the probing light have to be of equal size in order that destructive interference can occur (see the hatched areas covered by the incident beam in Fig. 13.55(b)).

13.11 The Optical Computer

Optical transistor : transphasor

-The main element of a transphasor is a small piece of nonlinear optical material which has, similar to a laser, two exactly parallel surfaces at its longitudinal ends

- If the length between the two windows just happen to be an integer multiple of half a wavelength of the light, then constructive interference occurs and the amplitude of the light in the cavity increase rapidly (Fig 13.56a)

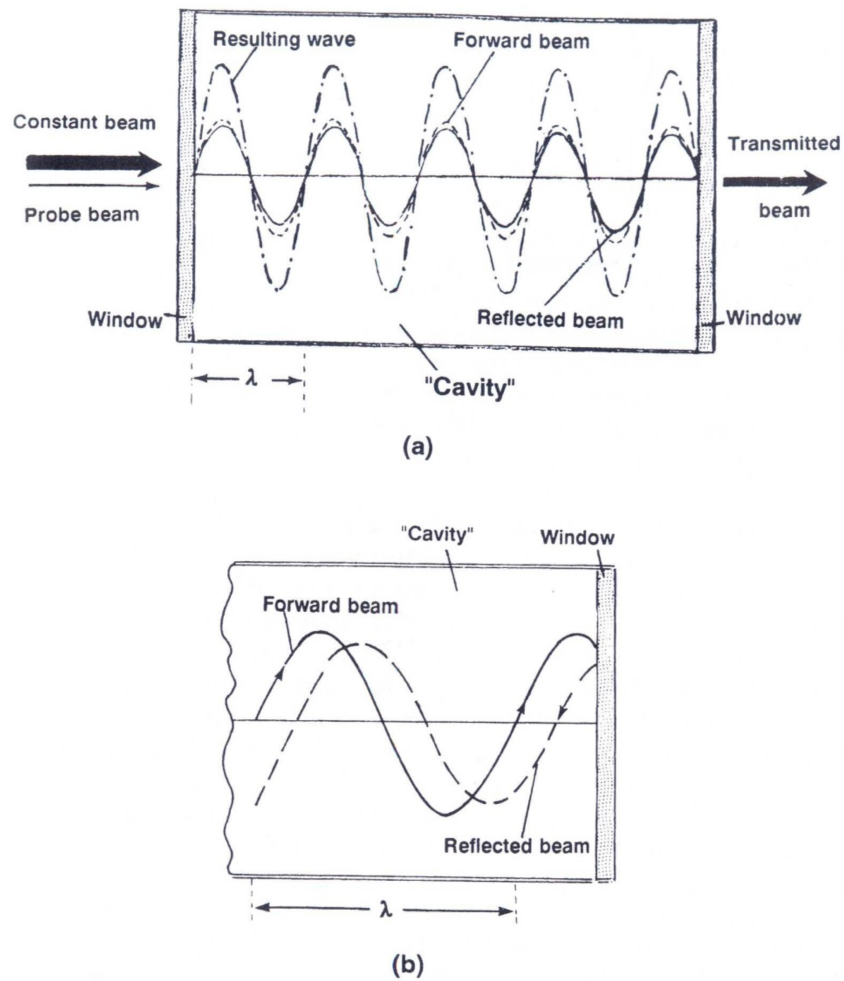


Figure 13.62. Schematic representation of some light waves in a *transphasor*. The reflectivity of the windows is about 90%. (a) Constructive interference. The length of the "cavity" equals an integer multiple of $\lambda/2$. (b) Condition (a) above is not fulfilled. The sum of many forward and reflected beams decreases the total intensity of the light. (*Note*: No phase shift occurs on the boundaries inside the "cavity", because $n_{cavity} > n_{air}$.)

13.1 Measurement of the Optical Properties

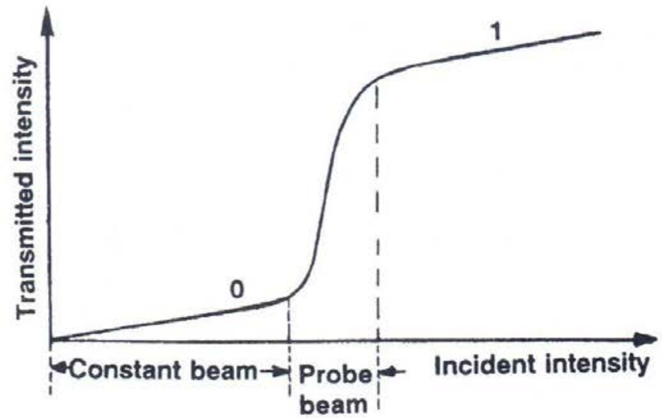


Figure 13.63. Schematic representation of an optical AND gate as obtained from an optical transistor (transphasor) constructed from a material with nonlinear refractive index. The low transmission state may represent a "zero" in binary logic, whereas the high transmission of light may stand for a "one."

- The key ingredient of a transphasor is a specific substance which changes its index of refraction as a function of the intensity of light, the index of refraction is

$$n_{med} = \frac{c_{vac}}{c_{med}} = \frac{\lambda_{vac}}{\lambda_{med}}$$

13.12 X-Ray Emission

$$E_{max} = eV = h\nu = \frac{hc}{\lambda} \Rightarrow \lambda = \frac{1240}{V} \text{ (nm)}$$

Voltage dependence of several white X-ray spectra

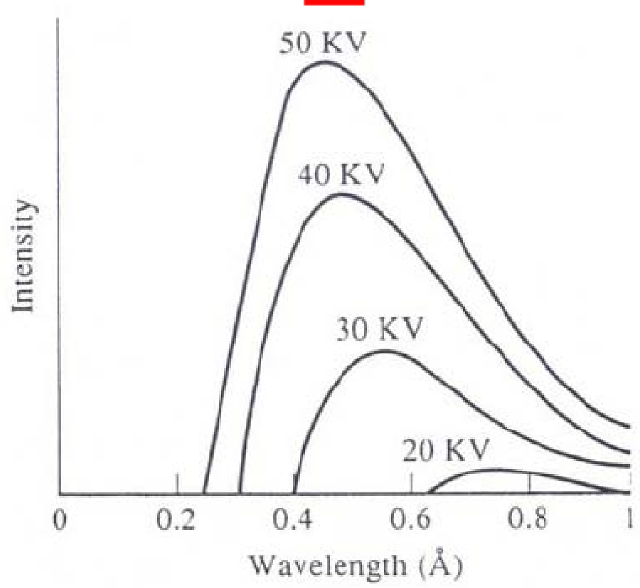


Figure 13.64. Schematic representation of the wavelength dependence of the intensi of white X-ray emission for selected acceleration voltages.

The wavelength of characteristic X-rays depends on the material on which the accelerated electrons impinge

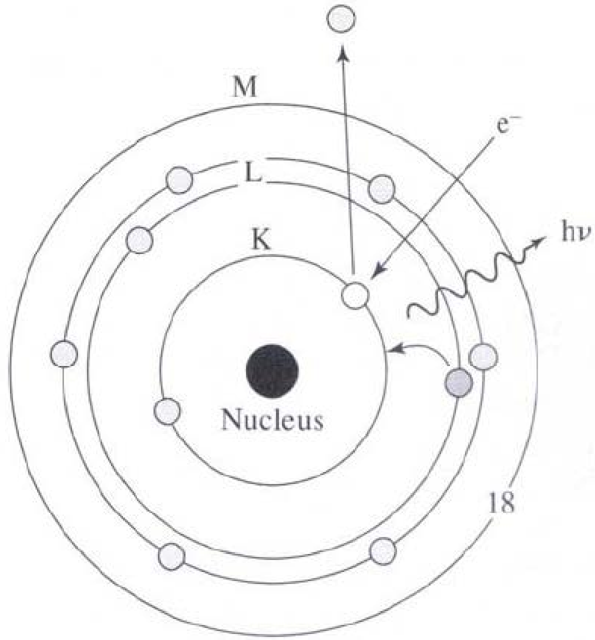


Figure 13.65. Schematic representation of the emission of characteristic X-radiation by exciting a K-electron and refilling the vacancy thus created with an L-electron.