3.15
LEDs and Lasers

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References: Pierret Chapter 9.4, article on LEDs from MRS BulletinOct. 2001 p764, and Solymar and Walsh chapter 12 for lasers

Luminescence mechanisms

Cathodoluminescence (light from electron bombardment)
  ZnS +Ag (blue), (Zn,Cd)S +Cu (green), Y_2O_2S +Eu,Tb (red)
Photoluminescence (light from UV irradiation)
  phosphors, TiO_2
Electroluminescence (light from electrical excitation)
  LED or semiconductor laser

<u>LEDs</u>: recombine e+h at a pn junction in forward bias: direct or indirect band-to-band recombination, at a trap or impurity center, or at an exciton. Color is determined by the band gap. Changing the composition of III-V or II-VI materials controls the band gap. Lattice parameter is important because it determines how well the material grows on a substrate, i.e. how many defects may be present.

  Red: direct gap $(Al_xGa_{1-x})As$; for 670 nm (1.85 eV) use x = 0.5
  Green: N-doped indirect gap GaP, where the N introduces a trap level,
    or direct gap (AlInGa)P
  Blue: indirect SiC,
    or direct InGaN or AlGaN, 450 nm (2.75 eV)
  IR: InGaAsP for 1.1 – 1.7 eV

Use heterojunctions to minimize reabsorption of light.

<u>Lasers</u> (light amplification by stimulated emission of radiation), an optical amplifier:

  probability of absorption = B_{13}
  probability of stimulated emission (makes coherent light) = B_{31}
  probability of spontaneous emission = A_{31}

Light can be amplified if stimulated emission exceeds spontaneous emission

If N_1 atoms are at energy level 1, N_3 are at energy level 3, $E_{31} = h\nu_{31}$ is the energy difference between levels 1 and 3, and $\rho(\nu_{31})d\nu$ represents the number of photons present with frequency ν_{31} in a spectral band of width dν (i.e. $\rho(\nu)$ is the photon energy density) then

rate of photon absorption in range dν $R_{13} = N_1 B_{13} \rho(\nu_{31}) d\nu$

rate of photon emission in range dν $R_{31} = N_3 B_{31} \rho(\nu_{31}) d\nu + N_3 A_{31} d\nu$

at equilibrium, $R_{13} = R_{31}$

also $N_3 = N_1 \exp(-h\nu_{31}/kT)$

therefore $\rho(\nu_{31}) d\nu = A_{31}/\{ B_{13} \exp(h\nu_{31}/kT) - B_{31} \} d\nu$

Planck's expression for black body radiation gives the photon energy distribution, for all ν

$$\rho(\nu) d\nu = \{8\pi h\nu^3/c^3\}/\{\exp(h\nu/kT) - 1\} d\nu$$

Comparing the two expressions implies

$$B_{13} = B_{31}$$

and $A_{31}/B_{31} = 8\pi h\nu^3/c^3$ (Einstein relations)

Usually $N_3 < N_1$ so absorption occurs more often than spontaneous emission. To make an amplifier, we need a population inversion, i.e. $N_3 > N_1$, to produce a gain > 1. $N_3 > N_1$ ensures that stimulated emission exceeds absorption.

gain = number of photons produced per incident photon

$\propto (N_3 - N_1) B_{31} \rho(\nu_{31}) d\nu$

Gain exceeds 1 over a small range of wavelengths around ν_{31}.

A population inversion can be produced in a three or four level system by pumping atoms up to a high energy level, from which they slowly decay into a lower level. Pumping requires a higher energy than $h\nu_{31}$.

Energy states in a Nd^{3+} atom in Nd:YAG laser make a 4-level system, which lases at 1.064μm (IR)

Energy states in a Cr^{3+} atom in ruby laser make a 3-level system, which lases at 693nm (red)

To raise gain we also need to increase $\rho(\nu_{31}) d\nu$ which is done by confining the light inside a cavity, length d; this ensures that stimulated emission exceeds spontaneous emission.

cavity modes exist when $\nu = c/2Nd$, N an integer.

Semiconductor lasers

A p+n+ degenerate junction can give a population inversion (need more electrons in conduction band than in valence band for population inversion). At low forward bias it acts as a LED, but when the applied voltage > bandgap it can act as a laser.

More efficient to use a heterostructure to trap carriers in a small region. Note in heterostructures when bands join, there is a band offset (ΔE_c or ΔE_v).

example: n-AlGaAs – GaAs – p-AlGaAs laser.

e&h are injected into the GaAs region and cannot escape. Light is also confined due to the difference in refractive index. Cavity is defined by cleaving the crystal. Cladding and active region need a good lattice match to avoid defects.

Blue lasers: ZnSSe cladding, CdZnSe active, or
AlGaN cladding, GaInN active.