Notes – Optoelectronics

PHY-U371, Electronics for Scientists, D. Heiman, 10/29/2007

- **Optoelectronics** – combines optical with electronics, O-->E or E-->O

- **What for?**
    - Memory (CD ROM)
    - Laser printers
    - Communications (fiber optics)

- **Why Optoelectronics for Communications?**
    - Multichannel – different, independent wavelengths
    - Highspeed – picosecond pulses, > GHz bit rates
    - Ease of coupling to electronics

- **Light Spectrum and Vision** –Chromaticity Diagram

- **Spectral Response of Semiconductors** – Semiconductor ***Bandgap***

- **Light Detectors** – Photovoltaics (photodiode or solar cell)

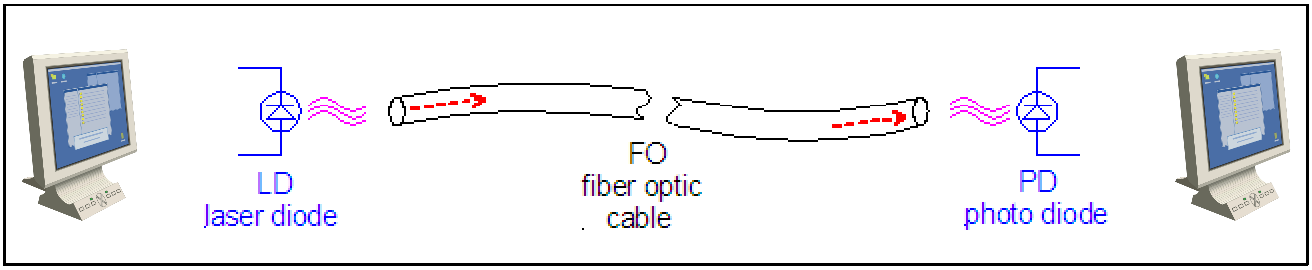
- **Light Emitters** – LED, Laser Diode, Ruby Laser

Fiber Optic Communication System

High-speed laser diodes and detectors are key elements in optical communications. Short light pulses of picosecond duration (few cm long) are sent through glass fibers to transmit digital data.

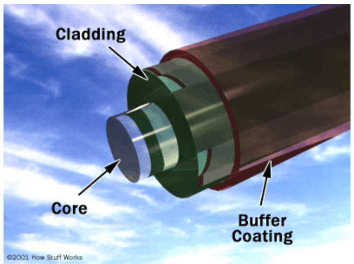
Fiberoptic (FO) systems are routinely used for long distance telephone and internet communications – and they are presently being implemented for shorter distances. The FO communication system illustrated below contains:

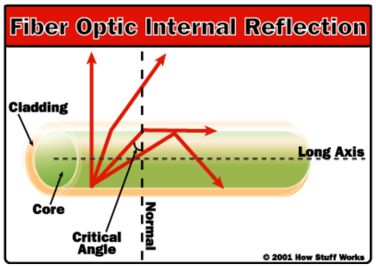
(*i*) a laser diode (LD) which is electrically modulated (on/off) with the digital input information;
(*ii*) a FO cable for transmitting the light pulses; and
(*iii*) a photodiode to convert the light pulses back into electrical pulses.

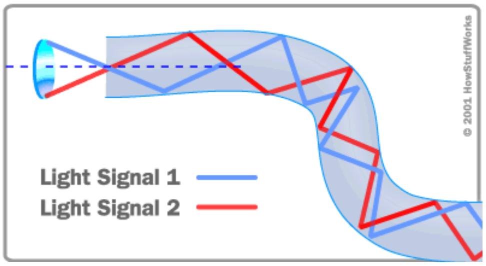


Most long-haul FO systems use light pulses generated by a GaInAsP semiconductor laser diode operating at 1.55μm wavelength where the optical absorption in the glass FO is minimum. In a 10GHz system the pulses are only a few cm in length. These pulses are transmitted through single-mode fibers of optical glass (SiO_2=silica=quartz) having a core diameter of about 6-8 μm. At the receiving end of the optical fiber the pulses are detected by a high-speed Si or InGaAs photodiode which converts the encoded light pulsed back into electrical pulses.

The illustrations below show: (left) construction of a FO cable where the light passes through the glass core region; (center) internal reflection inside the glass fiber; and (right) transmission of light inside the FO core. Light is confined inside the core by total internal reflection for angles greater than about 70 degrees from the normal. For light to exhibit total internal reflection, the cladding layer must have a smaller refractive index than the core region.



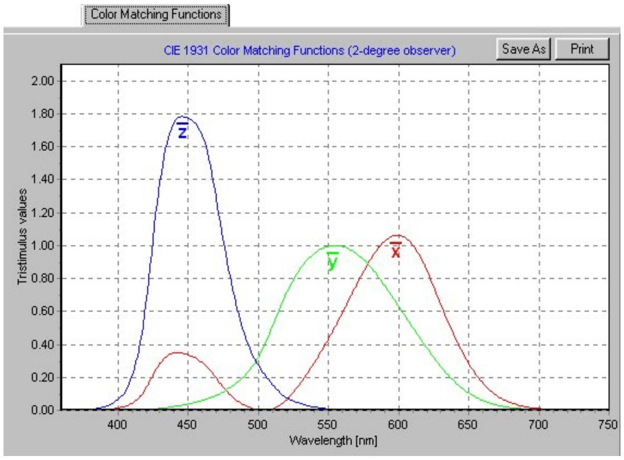




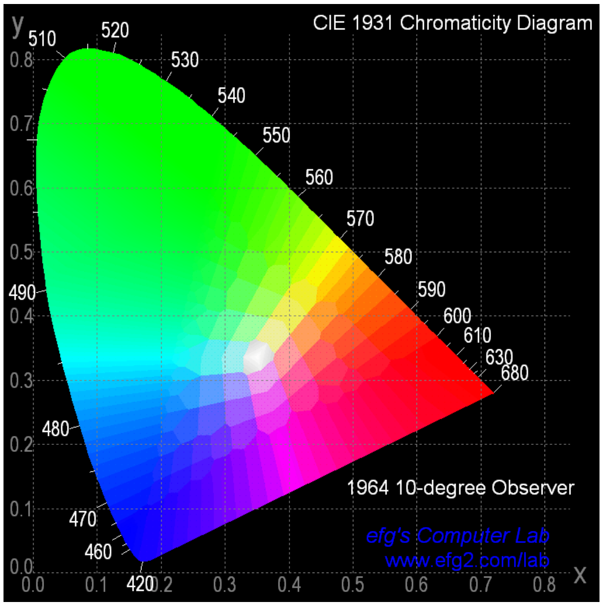
Chromaticity Diagram

All the possible colors of light which the human eye can distinguish can be made by adding relative amounts of the three additive ***primary*** colors: red, green and blue. These are related to the three wavelength-dependent photoreceptors in the human eye (cone cells). These three colors are also used in TV and computer color monitors.

In the mid-19th century, J.C. Maxwell first described a diagram, the Maxwell triangle, to quantitatively represent all possible colors using the three primary colors. Spectra of the three particular primary colors are shown on the left. The Maxwell triangle has been updated into the universally accepted CIE chromaticity diagram, shown on the right. In this diagram, the x- and y-axis are the relative amounts of red and green light, respectively, and the amount of blue is 1-x-y. The outer rim of the "tongue" shape represents pure or saturated colors (*hues*), and is light of a single wavelength. Going inward from the edge towards the center is equivalent to adding white light, referred to as changing the *tint*. Pure white light is composed of an equal mixture of the three primary colors, x=y=z=0.33. Note that the light from the green laser used in the experiment (530nm) lies on the upper, outer edge at x=0.21 and y=0.77. It is interesting that after dark you can see many variations of "white" lights that are distinguishable.



Spectra of the three colors,
the CIE 1931 Color Matching Functions.



http://www.efg2.com/Lab/Graphics/Colors/Chromaticity.htm

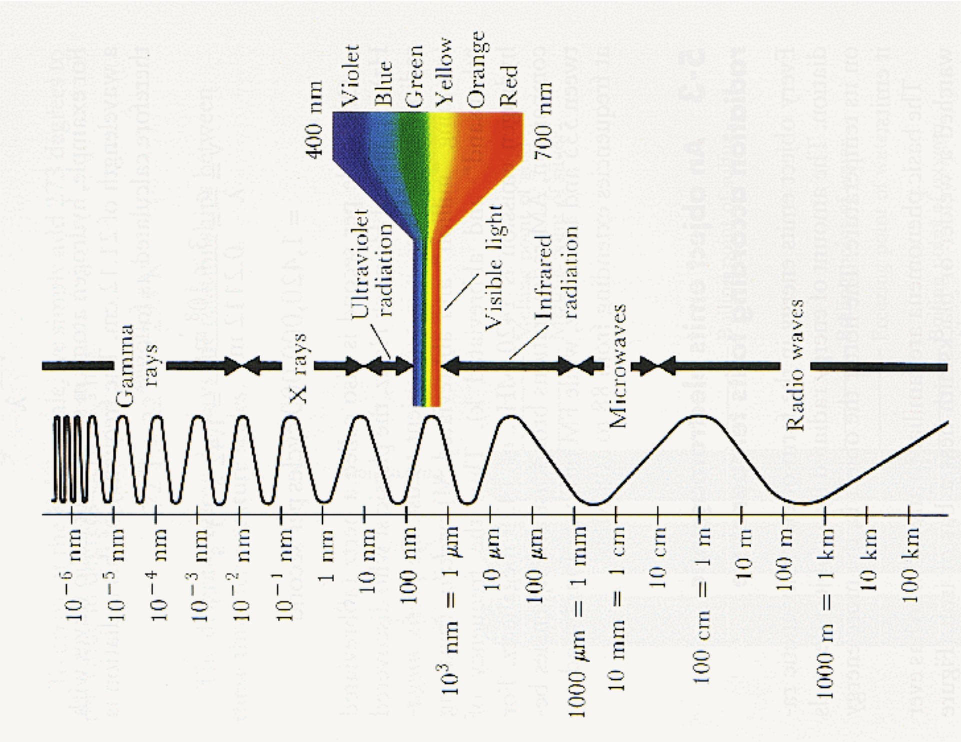
Spectral Response of Semiconductors

The energy of a photon (hc/λ) needs to bridge the bandgap energy (E_g) of a semiconductor to create an *e-h* pair,

$$hc/\lambda > E_g$$

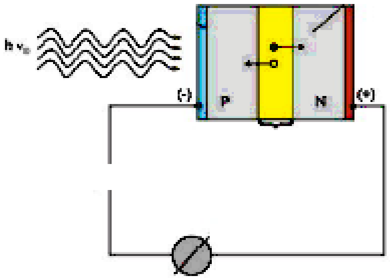
The table shows the bandgap energy and wavelength of various semiconductors

Material	E_g (eV)	λ (µm)
HgCdTe	0.12 eV	10.6 IR
InSb	0.25	5
Ge	0.7	1.8
Si	1.12	1.1 near-IR
GaAs	1.42	0.9
GaP	2.3	0.5 green
ZnSe	2.8	0.44
GaN	3.4	0.36 UV



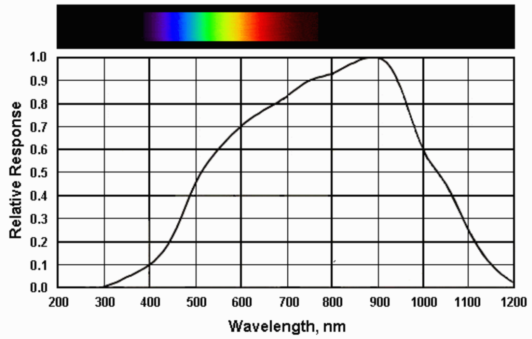
Light Detectors

Silicon photovoltaic or photodiode (solar cell)



pn-junction semiconductor diode (photodiode)

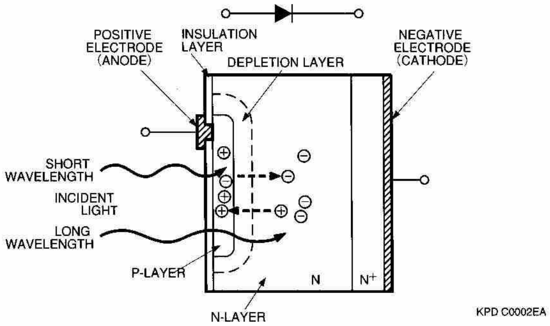
A photodiode is a *photocurrent device*
since light generates electron-hole pairs



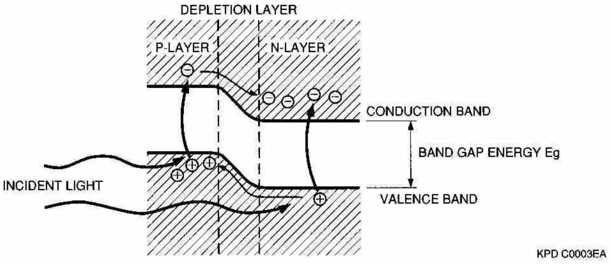
Typical Silicon Photodiode Spectral Response

Photocurrent is proportional to the number of photons
Responsivity is rated in amps/watt
Silicon has maximum responsivity of ½ A/W

One watt of blue optical power contains $2\text{x}10^{19}$ photons



(b): Photodiode P-N Junction State



Light is absorbed in the depletion region
of the photodiode
The electric field in depletion region
sweeps *e* and *h* into the *p* and *n* regions,
thus a charge appears at the contacts
which becomes a current in a circuit

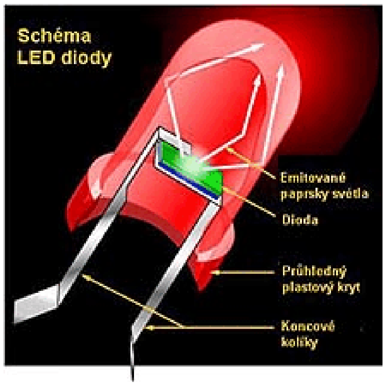
Photocurrent flows in the *backwards direction*

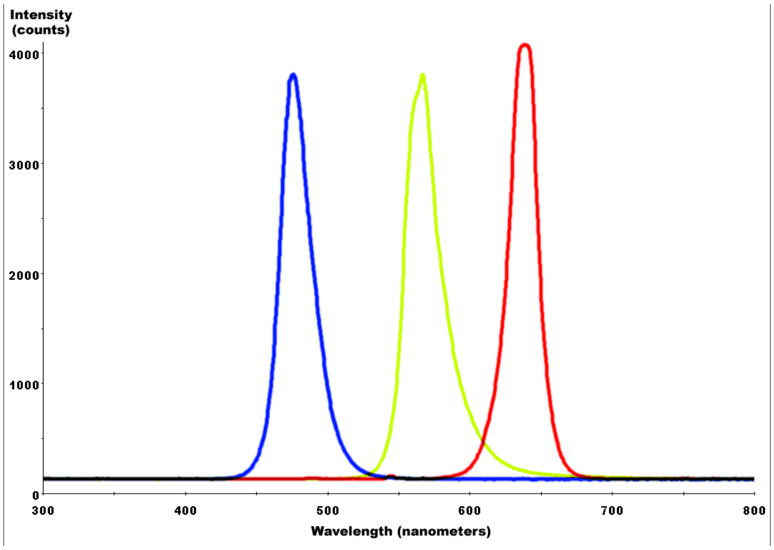
LED – Light Emitting Diode and LD – Laser Diode

Forward-biased *pn*-junction diode produces light of a single wavelength, but is broad $\Delta\lambda \sim 30\text{-}40$ nm

Emitted Wavelength – The photon energy is approximately equal to the “bandgap” of the semiconductor.

$$\hbar\omega = \mathbf{hc}/\lambda \approx \mathbf{E_g} \text{ in eV}$$





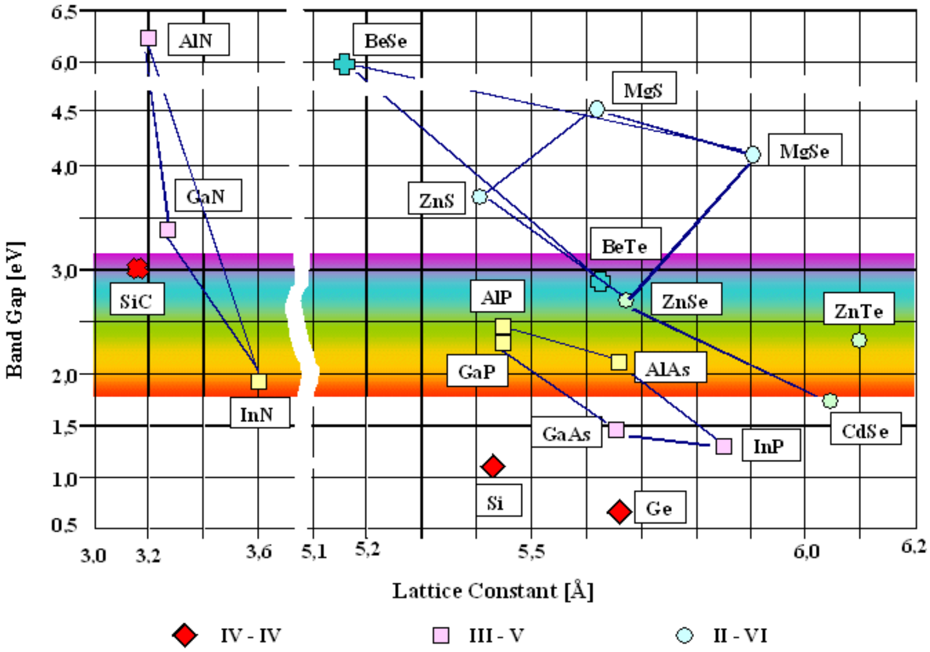
Change wavelength of LED by alloying semiconductors, such as $GaAs_{1-x}P_x$ or $Ga_{1-x}Al_xAs$

Example: $GaAs_{1-x}P_x$ (IR to green) $E_g = E_g^{GaAs} + x(E_g^{GaP} - E_g^{GaAs})$

$$E_g^{GaAs} = 1.42 \text{ eV}$$

$$E_g^{GaP} = 2.26 \text{ eV}$$

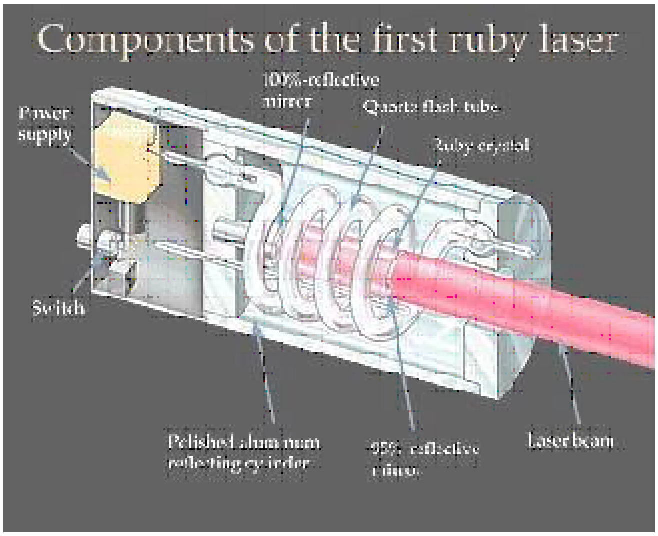
$$\mathbf{E_g\ (eV) = 1.42 + 0.84x}$$

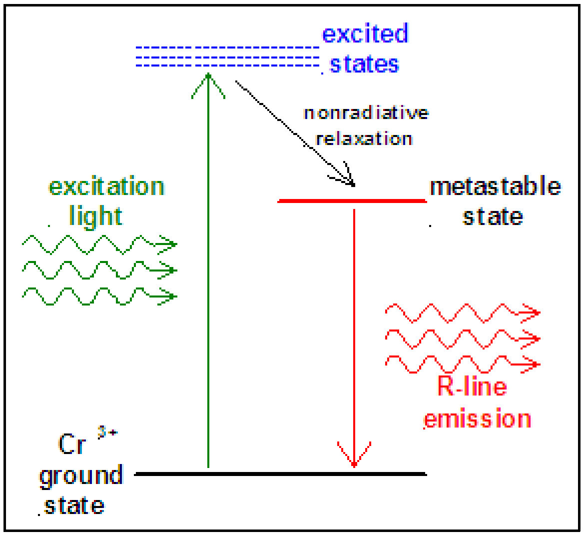


World's First Laser: The Ruby Laser

The laser was invented in 1960 by Theodor Maiman. This first laser was constructed of a cylindrical ruby crystal surrounded by a photographic flash lamp, all contained in a polished aluminum cylinder (on left). The flash lamp was used to excite the chromium ions in the sapphire host crystal. As the excited Cr(3+) ions de-excite they emit light as individual photons. Then as these photons travel back and forth in the optical cavity between the mirror-coated ends on the crystal, they induce other excited Cr ions to de-excite causing "stimulated emission." Rapidly, all of the ions become de-excited and generate a lasing light pulse. The light beam is *coherent* in the sense that the photons all travel in the same direction and have the same *phase*. LASER is an acronym for Light Amplification by Stimulated Emission of Radiation.

This type of laser requires three energy levels, as shown in the diagram on the right. Absorbed pump light excites the Cr^{3+} ion into excited states. The lifetime of these levels is short (50 ns), so that the excited ion quickly relaxes by making a transition to the long-lived metastable state. The energy which is lost in this process is nonradiative and goes into heating the crystal by generating *phonons* or vibrational excitations of the crystal atoms. The metastable energy level must have a lifetime which is long enough to enable the Cr ions to remain excited until a photon having the precise energy comes along to de-excite it. This lab experiment does not produce lasing in ruby, but investigates the excited states via the absorption spectrum and spontaneous fluorescence.





The lasing line in ruby is the so-called "R-line" having a wavelength of 694.3 nm. The fluorescence lifetime of the R-line is 3.5 ms. Fluorescence of the R-line can be excited by light in any of three absorption bands, at 250, 410, and 550 nm. A green laser operating at 530 nm is used here for exciting the R-line fluorescence.