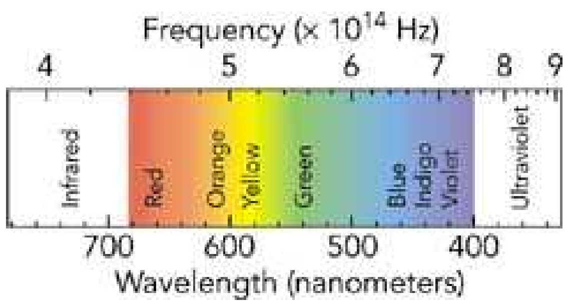
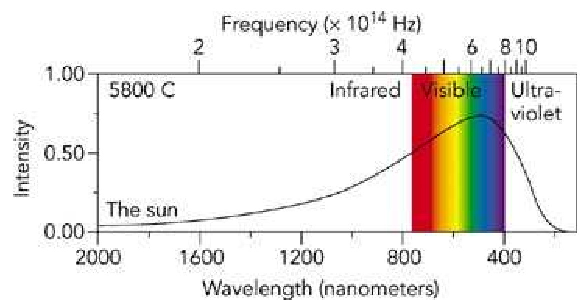
Sunlight and Electromagnetic Waves

We have seen that electromagnetic waves can have wavelengths from kilometers to the size of the atomic nucleus. A certain range of wavelengths that are detected by are eyes are called the 'visible' spectrum. We normally label these wavelengths by color e.g., red, yellow, green etc. Colors just denote different wavelengths. Since the speed of light,c, is almost 3 x 10^8m/s in air, colors also define the frequency of light. The visible spectrum ranges from $\approx$ 400 nm (violet) to $\approx$ 700 nm (red). A 'nm' is a nanometer (10^{-9} m) or one billionth of a meter. Since $c = \lambda f$, the frequencies range from $\approx 10^{14}$ Hz to 10^{15} Hz





The frequencies associated with the visible light are much too large to be generated with a LC (tank) circuit or magnetron. Light is created when charged particles (normally electrons) in atoms vibrate (oscillate and accelerate). When electrons jump around in their orbits, the oscillations can occur at frequencies of $\approx 10^{15}$ Hz. Sunlight comes from the outer layer of the sun called the photosphere. The temperature of the photosphere is 5800K which gives a black-body spectrum which peaks in the green part of the visible spectrum. At this temperature, the atoms are ionized. The collisions of the electrons and nuclei produced the shaking required to produce the black-body radiation we see as visible light.

In vacuum, the speed of light is c = 3 x 10^8 m/s. When light travels through a transparent medium, the speed is no long c but some other smaller speed, v. This speed depends on the material. The ratio of the these speeds is called the **index of refraction, n**:

$$n = \frac{c}{v}$$

The index of refraction depends on the material. The term 'refraction' refers to the fact that the direction of the light changes when it goes from one medium to another. Air (n = 1.0003) and most gases have an index very close to one i.e,, light in gases moves with almost the speed of light, c.

Rayleigh Scattering - Why the Sky is Blue

The air is made up of molecules (mainly nitrogen and oxygen) and dust particles of all sizes. When light travels through a transparent gas like the air, the molecules are effected by the electric field of the light. The molecules in the air are much smaller than the wavelength of light. (Atoms are a few tenths of a nanometer.) When a light ray passes an air molecule, it polarizes the molecule and 'shakes' it back and forth in the direction of the electric field. This absorbs some of the visible light and re-radiates the energy of the original light. This re-radiated light is 'scatter' in new directions more or less isotropically.

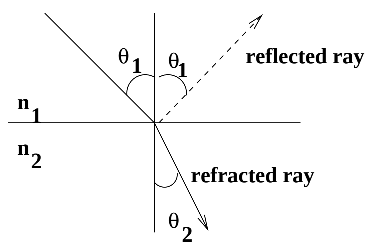
How well the light scatters the original light light depends on the wavelength of the light. Since the molecules are so much smaller than the wavelength of light, the molecules are poor antennas. A good antenna would be $\frac{\lambda}{4}$ or even $\frac{\lambda}{2}$. Since red light has the longest wavelength, air molecules Rayleigh scatter light less than blue light i.e. blue light Rayleigh scatters more than red light.

Most of the sun light does not scatter in the atmosphere. Of the light that does scatter, most of the scatter light is blue. This gives the sky it blue color. Without Rayleigh scatter in the atmosphere, the sky would be black.

Rayleigh scattering also explains why the sunset is red. When the sun is going down, the sun light comes in almost tangent to the surface of the earth. The light has to travel through a lot more air. Nearly all of the blue light is scattered from the incident sun light leaving only the longer wavelengths i.e. red light.

Snell's law and Rainbows

When light passes from a medium with an index of refraction, n_1 to a second medium with an index of refraction of index, n_2, the direction of the light is changed.



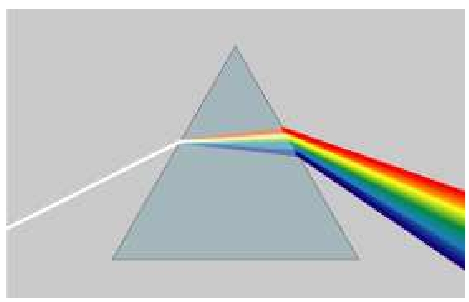
The relationship between the incident and outgoing refracted rays is given by **Snell's law**:

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

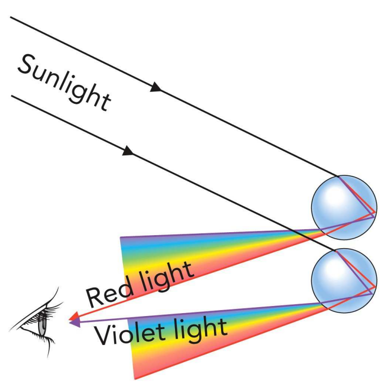
Notice that the angles are measured with respect to the normal to the interface between the two mediums. Snell's law is a consequence of light traveling at different speeds in different mediums.

The frequency of the light stays the same in different medium. Since v $= \lambda f$, the wavelength, λ, changes when the velocity changes.

The index of refraction of a material not only depends on the transparent material but also on the frequency of the light. Blue light refracts slightly more than red light. This effect is called **dispersion**. For example, a common type of glass (Crown glass) has an index of refraction of 1.54 for blue light but an index of refraction of 1.52 for red light. This difference in refraction allows a prism of refracting material to produce a rainbow spectrum.



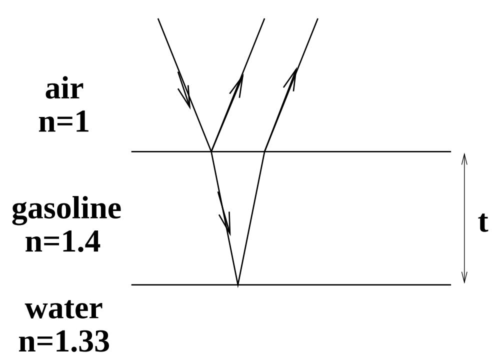
Dispersion is what leads to a rainbow in the sky after a storm. When sunlight travels straight through a circular rain drop (left figure), the angle of incidence is 90^o and no refraction occurs. However, light which is 'off center' (right figure), the angle of incidence is not 90^o and the light refracts going into the rain drop and when it exits the rain drop. Dispersion of the light during the refraction separates the light into bands of color we call a rainbow.



Thin Film Interference

Some of the light can be **reflected** when striking the interface between the two medium. Normally only a couple of percent of the light is reflected when going from one medium to another. This reflected light makes an angle of θ_1 on the other side of the normal. When light transitions between two materials with different wave speeds, the **impedance mismatch** leads to part of the wave being reflected. Impedance is a measure of the materials opposition to the passage of the light. (Impedance is a turn also used like resistance to an AC current i.e. the impedance of a capacitor to the flow of an AC current).

We have all seen the 'rainbow color' pattern from oil or gasoline on water. This is an interference pattern caused by the oil when it spreads out to form a very thin layer.

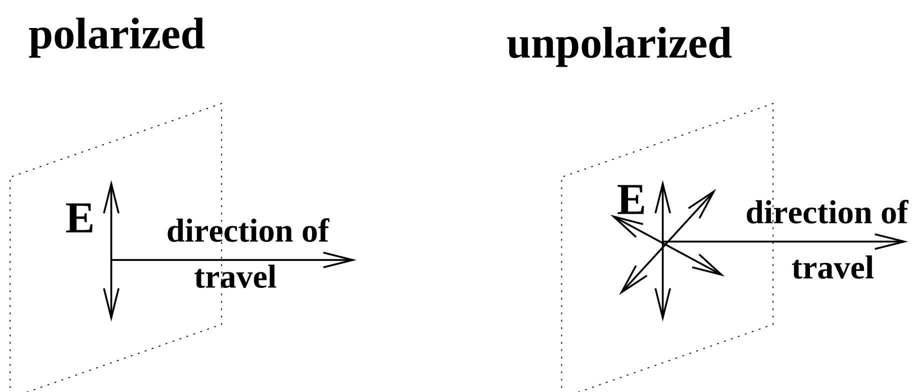


Light enters the gasoline layer. Some of the light is reflected. The light travels to the water gasoline interface where some more of the light is reflected back up and through the air gasoline interface. For light that enters almost perpendicular to the interface, the extra path length for the light is twice the thickness of the gasoline film. The same effect happens with soap bubbles.

The light that is reflected back from the top surface and the bottom surface will then interfere with one another. If the light is a single wavelength, the pattern of interference is dark and light bands (destructive and constructive interference). Since the effect depends of the thickness of the thin film and the wavelength of light, for white light the resulting pattern is a rainbow (dispersion pattern).

Polarization and Sunglasses

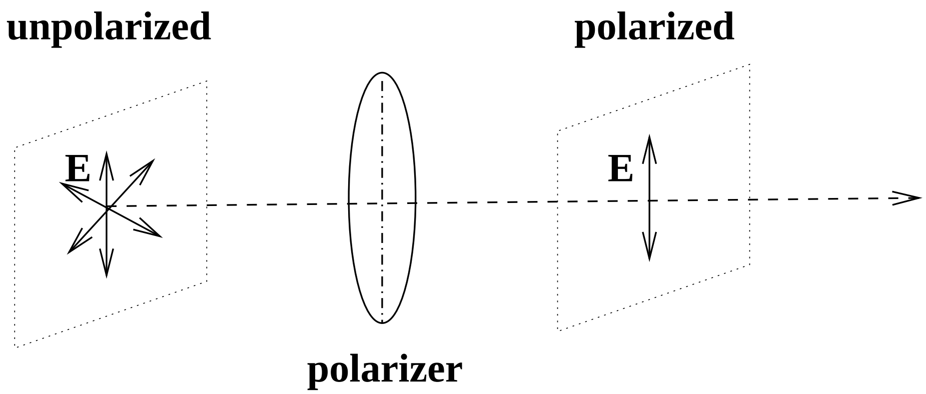
The **transverse** nature of light waves means light can be **polarized** Polarization means the electric field (or magnetic field) is oriented in a particular direction. In normal **unpolarized light**, the electric field is at random directions perpendicular to the direction of propagation.



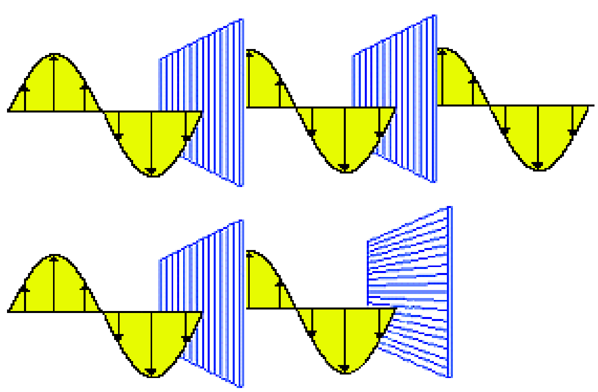
If the electric field vibrates in a single direction, the light is called **polarized**.

A material which stops light except that part of the light which has its electric field oriented in a particular direction is called a polarizer. The direction which passes the light is called the **transmission axis** of the polarizer. A polarizer will pass $\frac{1}{2}$ of the incident intensity. We can understand this if you consider the electric field as random in the un-polarized light incident on the polarizer.

At any given direction there is some component of E parallel to the transmission axis as well as a component perpendicular to the transmission axis. On average $\frac{1}{2}$ of the light is absorbed and $\frac{1}{2}$ transmitted through the polarizer.



One polarized light has been produced by a polarizer, a second polarizer can be used to change the direction of polarization and adjust the intensity. The second polarizer is referred to as the **analyzer**. If the analyzer has the transmission axis in the same direction as the first polarizer, all of the light will be transmitted through the analyzer. If the analyzer is at 90^o to the original polarizer, no light will pass through the analyzer.

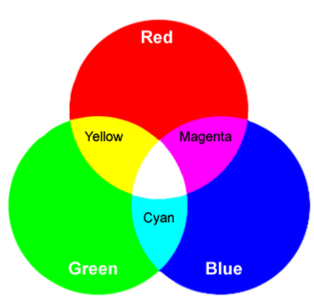


Reflected sunlight is (partially) polarized, especially when reflected from a horizontal surface. This is why people often wear Polaroid sunglasses. The polarizer lenses reduce the light intensity without changing the colors and cut out more of the reflected 'glare' caused by light reflected from horizontal surfaces.

Primary Colors

Color is an illusion created in our eyes. When light strikes the retina of your eye, your eye is not directly detecting the wavelength of the light. The retina has rod cells which are very sensitive to light but do not detect color. Rod cells are for low light situations (night vision). The cone cells do detect different wavelengths of light. Different cone cells detect light at $\approx$ 600 nm for red light, $\approx$ 550 nm for green light and $\approx$ 450 nm for blue light. This does not result in just seeing three colors. The human eye can distinguish hundreds of colors (and hues). If light with a wavelength of 575 nm strikes the retina, both the red detecting and green detecting cone cells are activated so that we see yellow. If equal intensities of 600 nm light and 550 nm light strike the retina, the eye detects yellow light.

Red, green and blue are know as the primary colors. Using combinations of red, green and blue, almost any color can be created.

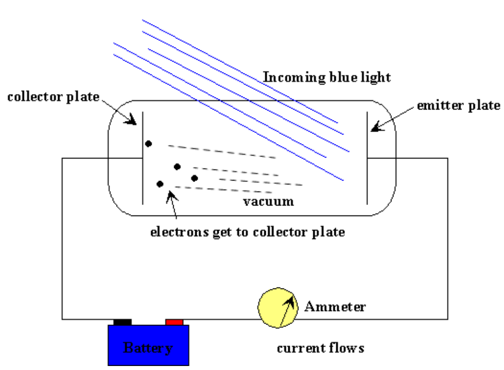


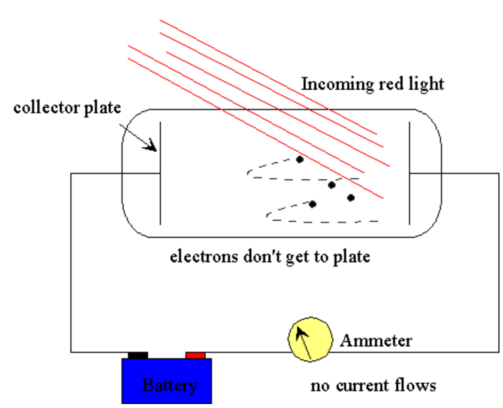
This is how color television and computer monitors created color images. Each 'pixel' (in effect a tiny dot on the screen) is made up of a red, green and blue element. If the pixel is supposed to be yellow, the red and green elements are turned on with equal intensity. White is made up of equal intensities of all three primary colors. Cyan, Magenta and yellow are called the primary subtractive colors. When one of these colors is applied to a white surface, it absorbs (or subtracts) one of the primary colors from the reflected surface. For example, cyan subtracts the reflection of red.

Quantum Physics and Wave-particle Duality

In the first couple of decades of the 20^{th} century Niels Bohr and others explained the basic structure of the atom but at the cost of questioning major aspects of Newtonian physics.

To understand how electrons move in solids, we have to understand some principles from **quantum mechanics**. In the same year that Albert Einstein published the special theory of relativity (1905) , he published a paper concerning the interaction of light with matter. When light of a certain frequency strikes a surface, the light comes in particle-like 'packets'. These packets are called photons.





The energy of each packet is given by the:

$$\mathbf{E} = \mathbf{h} \cdot \nu$$

where E is the energy, ν is the frequency of the radiation and h is Planck's constant. Planck's constant comes out of Max Planck's theoretical study of 'black body' radiation in 1900. That 'neat' little trick pops up again. (By the way, the value of Planck's constant is 6.626 x 10^{-34} Joules seconds.) After a century of work which showed that light was a wave, Einstein's analysis of the 'photo-electric' effect showed that light had particle-like properties. An interesting side note is that Einstein won the Nobel prize for his work on the photo-electric effect and **other work** .... not explicitly for relativity.

In 1923, a Ph.D. student name de Broglie at the Sorbonne in Paris proposed in his thesis that matter could be treated as a wave. Just a few years before Einstein had explained the photo-electric effect by treating light waves as particles (photons). The idea went full circle. Waves can be particles and particles can be wave. Both have wave properties and particle properties. This is know as **Wave particle duality.**

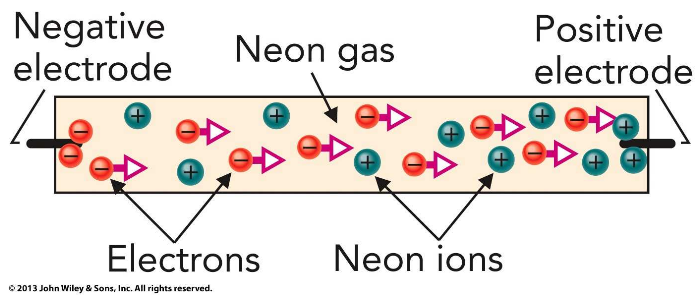
In fact, de Broglie proposed (which was quickly confirmed for the electron) that the 'wavelength' of an electron is given by:

$$\mathbf{wavelength} = \lambda = \frac{h}{momentum}$$

More Light bulbs

We have all seen 'neon' signs. Neon signs emit light in particular colors because of the atoms used in the discharge tubes, normally at low density. Actually, 'neon' signs are the bright red-orange colored signs. Other gases (argon, krypton, xenon, and helium) are used for other colors in 'neon' signs.

The color of the light from a neon light comes from electrons jumping between particular levels in the neon atoms after the atoms have been excited by the high voltage (10 kV) across two ('cold') electrodes inside the glass tube. The gas is normally at a low pressure (few mm of Hg pressure).



As we discussed earlier concerning light bulbs, fluorescent bulbs use this type of ultraviolet radiation from mercury . The ultraviolet light is then converted to visible light by a phosphor coating on the class tube. The process where the atoms of the phosphor absorb the ultraviolet light and re-emit the light at visible wavelengths is called fluorescence.

Fluorescence and 'neon' tubes are called discharge tubes. The are typically 6-10 times more efficient at creating visible light compared to an incandescent light with a filament.

Street lights use much denser gas. In a mercury street light (the blueish colored ones), the mercury is at much higher pressure than in a fluorescent bulbs. These lights still emit ultraviolet but the mercury atoms are dense enough to absorb the ultraviolet light. Eventually, this radiation trapping has so many atoms excited to the transition (level) that creates the ultraviolet (254 nm) light that the atoms can not emit the ultraviolet light but emits the light through visible transitions.

High pressure sodium street lights (yellow colored), use sodium vapor. The main spectrum of sodium is the 'D lines', which are two transitions both of which are yellow. With the high pressure and heat in the light, the lines get thermally broadened. The atoms are bouncing around so much the light gets spread out into a broad spectrum of yellow light.

Atoms

Quantum mechanics also explains the structure of atoms as well as the periodic table of the elements. Standing waves also form in atomic energy levels. Bohr first proposal was that electrons were stable in certain **orbitals'** or energy levels and only radiated light when they jumped or hopped from one orbital to another. The energy of the emitted photons is give by Einstein's relation $\mathrm{E} = \mathrm{h}\nu$. This explained simple atomic spectra like hydrogen. In elements with atomic number larger than hydrogen, the orbitals are filled in (starting with the lowest energy level) one by one because of the Pauli exclusion principle.

This alone do not completely explain the complexities of atomic spectra or the periodic table. To complete the picture, we must look at angular momentum. Examined carefully, each spectral line (color) is actually two or more (in some cases many) lines. Understanding this more intricate structure requires an understanding of atomic spectra and the periodic table.

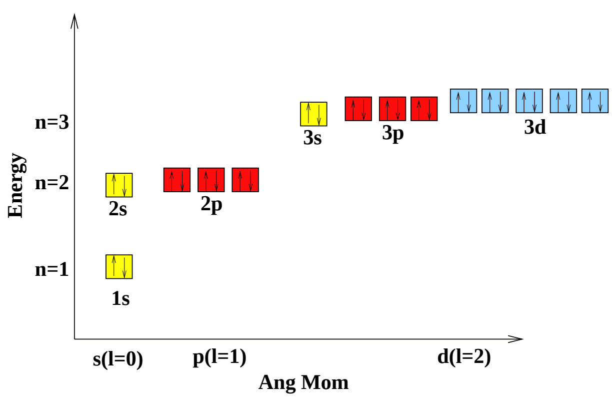
At the atomic level, angular momentum is 'quantized'. It comes in discreet amounts. There are actually two types of spinning that occur with electrons in their orbits around the nucleus.

The first and most obvious is the angular momentum due to the circular motion of the electron around the nucleus. The second type of spinning motion is the electron itself. Although the electron is thought to be 'point-like', i.e. electrons have no internal structure, it possess an intrinsic angular momentum like a spinning ball. This is called 'spin'.

The orbital angular momentum (in units of h) is labeled with notation used when atomic spectra lines were first studied.

Ang Mom (l)	label	Sub-states (m)
0	s (sharp)	1
1	p (principal)	3
2	d (diffuse)	5
3	f (fundamental)	7

For a given n, the number of possible angular momentum values is one less than the n (l=n-1). Furthermore, each value of l has 2l+1 sub-states. These sub-states denote azimuthal angular momentum or 'magnetic' quantum number and are labeled by 'm'.

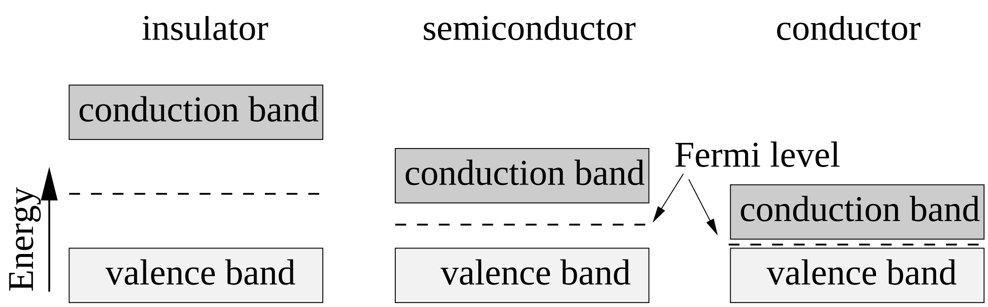


Electrons in Solids

Solid materials can be classified as conductors, semiconductors and insulators. In solids the nuclei are fixed but some of the electrons are free to more around depending on the material. **Wave-particle Duality** is fundamental to understanding how electrons move in solids.

Because of their wave like nature, electrons in a solid form bands of energy levels. These bands are **standing wave** patterns formed by the electrons in the solid. Electrons are fermions ('Fermi particles' or spin $\frac{1}{2}$ particles) and obey the **'Pauli exclusion principle'**.

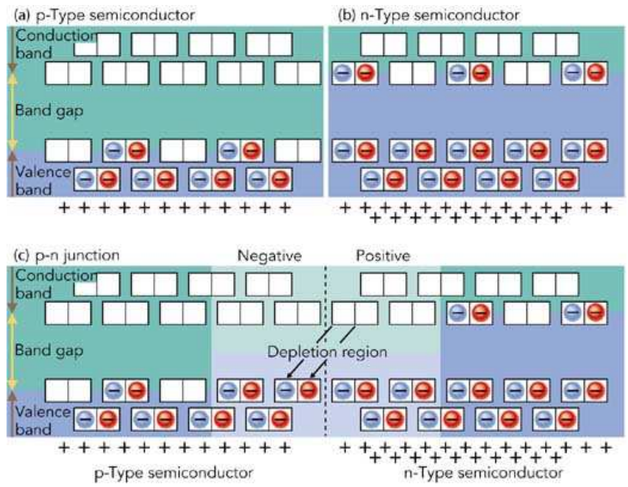
The "Fermi level" (dashed line in the figure) is the term used to describe the top of the collection of electron energy levels at absolute zero temperature i.e. how high the energy levels fill up at absolute zero.



Diodes

So far, we have discussed material that are assumed to be 'pure' materials. When a small amount of the right type of impurity is added to a semiconductor ('doped'), the proprieties of the semiconductor can be changed. If the impurity creates a few empty valence levels ('holes') the material is said to be a p-type semiconductor. If the impurity places a few electrons in the conduction band, the semiconductor is a n-type semiconductor.

Since the impurity and the semiconductors atoms are all electrically neutral, there is no net charge on the doped semiconductor.



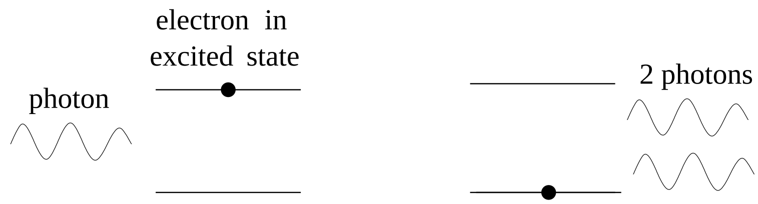
When an n-type and p-type semiconductor are placed in contact, the few extra electrons in the n-type fill in the holes in the valence band of the p-type. This leaves a depleted region between the p-type and n-type semiconductors and current can not flow through the semiconductor. However, if you apply a small electrical potential (0.6 volts in silicon) to the joined p-type and n-type something interesting happens. If the potential causes electrons move into the n-type material (and are removed from the p-type), the depleted region vanishes. This allows a current to flow and the 'p-n' junction diode conducts electricity. However, if the potential is applied in the opposite direction, the depleted region increases and no current will flow.

Lasers and LEDs

Lasers are used for many applications. Lasers are used to read the information from a CD or DVD. They are used by surveyors and even in levels for hanging pictures. The idea of a laser originated with some work by Einstein in 1917 and developed as a practical device in the 1960's. Lasing effects have even been observed in interstellar gas clouds.

'LASER' is an acronym for 'Light Amplification by Stimulated Emission of Radiation'. Stimulated emission is where a photon causes a atom in an excited state to emit another photon. With stimulated emission, the photons are all traveling in the same direction and the oscillation of the electric and magnetic fields are in 'lock step' between photon. The light from a laser is then 'coherent'.

Normally, electrons in excited states spontaneously drop to a lower energy level and emit a photon in the process. The result is light which is incoherent. With incoherent light the photons move in many directions and diverge. Each photon is oscillating randomly with respect to other photons.



For a laser to work, you need many atoms in a particular excited state. When many of the atoms are in a particular excited state (and not the ground or bottom state), a 'population inversion' exists. How to create a population inversion can be done in a few different ways called 'pumping'. One way is to excite the laser medium with a lot of photons. Another way is to pass an electrical current through a gas medium. Chemical reactions can also be used to exit many of the atoms to an excited state.

Once you have a laser medium with an excited state, one atom will spontaneously emit. This photon will then be amplified into many coherent photons as it passes through the laser medium. Normally, two mirrors are placed at each end of the laser medium. One mirror is nearly perfectly reflecting so the photons return to the laser medium for further amplification. The other mirror is partially 'silver-ed' like a two way mirror. Some of the photon beam reflect back into the laser medium. The remaining part passes through the semitransparent mirror as the extracted laser beam.

Laser can be made to be 'pulsed' or continuous waved (cw). A cw laser is continuously pumped and emits a continuous beam of laser light. A pulsed laser releases the light in one short pulse of light. Some of the pulses can be very short e.g. 10^{-15} seconds or less. Pulsed lasers normally use a 'Q' switch. A 'Q' switch' just stops the light from propagating by absorption until it changes to a transparent state allows the laser amplify the light and output a short pulse of laser light.

Light emitting diodes (LEDs) are semiconductor devices that emit light. Depending on the color of light desired, LEDs are normally made of gallium, arsenic, phosphorus or indium. When the diode is 'forward biased' i.e. in the conducting state, the electrons in the conduction band can jump to a valence band and emit a photon of light. Depending on the band gap in the particular semiconductor, the light can have almost any color. The band gap in eV (1 eV $= 1.6 \times 10^{-19}$ J which is the energy an electron gains going across a potential of 1 volt) determines the energy and thus the color of the light ($E = h f$). Silicon is normally not used for LEDs because the silicon ends up transferring most of the emitted light to heat. Combinations of LEDs which give white light will eventually replace most light bulbs. They are very efficient compared to a fluorescent or incandescent bulbs.

Laser diodes are semiconductor devices that emit laser light. To achieve the required population inversion, a high current is passed through a thin layer (less than 1 μ m) of a light emitting semiconductor. Mirrors can also be placed on either end like with a regular laser. The spontaneously emitted light from a few transitions can then be amplified by the semiconductor with the population inversions to produce laser light.