Optoelectronics

Overview

- In this lecture you will learn
- Basics of photodetectors
- Different types of detectors
- Modulators and other accessories
- Keywords: opto-electronic devices, photodetectors, modulators

Light Detection

- In the last lectures, we saw some of the important light sources for biophotonic applications. In this lecture we will briefly discuss the electronic detection tools that are used.

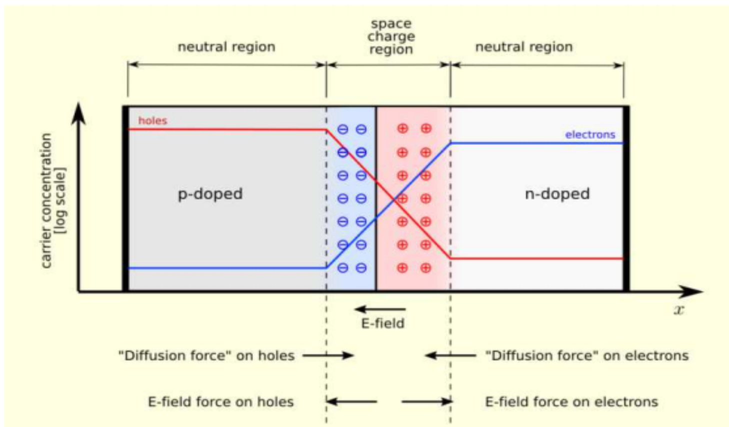
- Light detectors use photon to electron conversion in some way or the other, for e.g., using photoelectric effect, or by the creation of electron-hole pairs as in semiconductor diode junctions. There are single element detectors as well as arrayed detectors that can detect low light intensites. Amplification mechanisms such as avalance processes and photomultiplication processes are used to amplify low light signals.

Semiconductor Junction

- In the case of crystals, the discrete energy levels of molecule merge to form bands. The two important bands are referred to as valence band and conduction band. Valence band refers to the energy levels where the electrons are 'bound' to the nucleus, whereas conduction band refers to the situation where the electrons are 'mobile', i.e. they can hop from one position to another position in space freely. The difference between the top of the valence band and the bottom of the conduction band is called the bandgap.
- Materials can be classified in to metals, insulators and semiconductors by their bandgap. In the case of metals the conduction and valence bands overlap, so they are good conductors of electricity. In the case of insulators the bandgap is very large, so there are very few electrons available for charge conduction and therefore they are poor conductors.
- Semiconductors have an intermediate bandgap and it is possible to achieve good conducting behavior either at high temperatures (when valence electrons are excited to the conduction band) or by doping, which is the process of adding some impurity atoms to the semiconductor which donate free electrons (so are called donor atoms and the semiconductor crystal is called n-doped). It is also possible to dope acceptor atoms which take in an electron and thereby give a vacancy (a hole) that is mobile within the semiconducting crystal. This type of doping is called p-doped. In n-doped semiconductor, electrons are the majority carriers and in p-doped semiconductors, holes are the majority carriers. An electron-hole recombination is an interaction that takes place in semiconductors which happens with the emission of a photon. Similarly a photon can be absorbed creating an electron-hole pair. These interactions are made use of in semiconductor light sources and detectors.

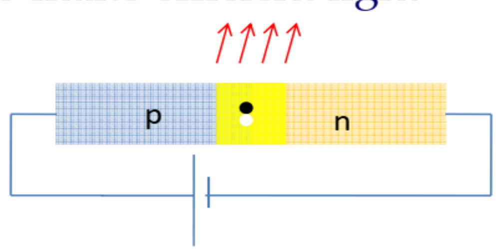
The pn Junction

- When an n-doped and p-doped semiconductor crystals are bonded a region called depletion layer gets formed at the interface as shown in the diagram, due to the concentration difference in holes and electrons in the two regions. The depletion region forms a barrier for conduction of charge through the barrier. The width of the depletion region can be controlled by biasing the junction, i.e. applying an external potential as shown in the next slide.



Forward Bias: Diode Lasers

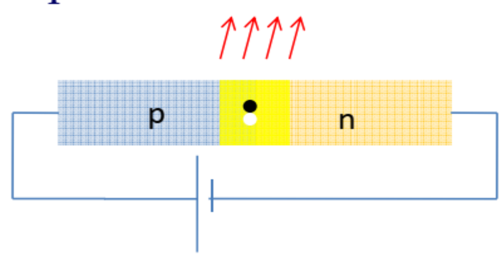
- When a pn junction is forward biased, i.e. positive terminal of a battery is connected to the p side and negative side to n side, holes from p side and electrons from n side are pushed to the depletion region where they recombine to emit photons. The recombination process is more efficient for a certain class of semiconductors called direct bandgap materials. An example of a direct bandgap material is Gallium Arsenide (GaAs). Silicon (Si) is not a direct bandgap material, so it can not be used to make efficient light emitting diodes (LEDs).



Light Emitting Diode & Diode Laser

Diode Lasers

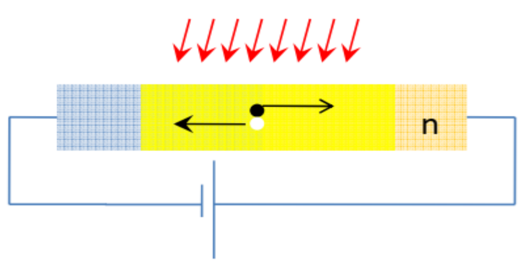
- In the presence of stimulated emission being dominant, one gets laser action from the diode junction and such a device becomes a diode laser. In practice single juntion devices are not efficient and therefore almost all diode lasers are multiple heterojunction devices. Diode lasers are very compact and can be mass produced easily which has enabled their use in consumer electronic products such as CD/DVD and other optical drives as well as in desktop printing and optical communications.



Light Emitting Diode & Diode Laser

Reverse Bias: Photodiodes

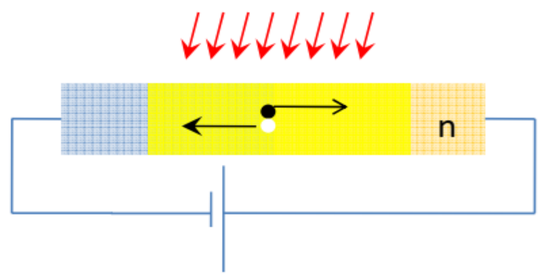
- In the reverse bias condition, as shown in the diagram below, light falling in the depletion region creates an electron-hole pair which get split by the electric field in the depletion layer and move in the direction as shown in the diagram producing a photocurrent. Typically a PIN structure (p type-intrinsic-n type) is used instead of a simple pn junction to increase the response time of detection.



Photodiode

Photodiodes

- Silicon photodiodes are commonly used in the visible region. For the production of electron-hole pairs in a semiconductor the photon energy must be greater than the bandgap energy so that it can be absorbed. For Si, the bandgap is 1.1 eV corresponding to about 1000 nm. So Si can be used to measure light with wavelength below 1000 nm, i.e. in the visible region.



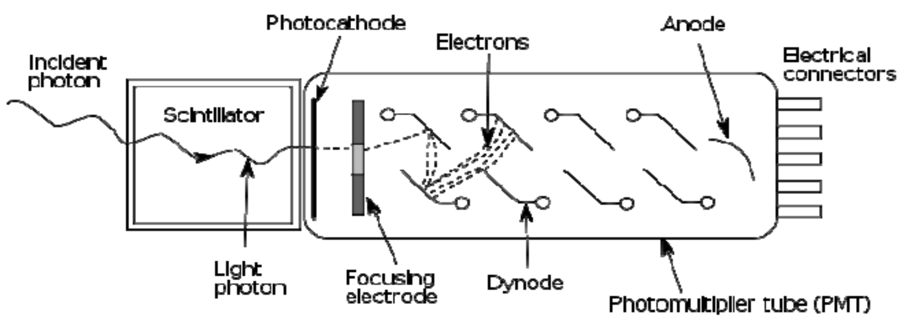
Photodiode

Avalanche Photodiodes

- In reverse bias there is no current flow due to the large depletion width. However when the reverse bias voltage is increased beyond a threshold a breakdown mechanism called the avalanche breakdown occurs in the pn juntion. In avalanche breakdown the applied electric field are so large that impact of an energetic electron with a bound electron-hole pair can free the electron and hole which travel to the opposite terminals producing a current. This process generates more electrons and holes that can participate in the avalanche process producing very high currents until material breakdown occurs. Avalanche photodiodes (APDs) operate above the breakdown voltage and use the avalanche process to amplify the photocurrent. They use high reverse bias voltages and by using high gain factors are able to detect very low light levels.

Photo-multiplier Tubes

- A photomultiplier tube (PMT) is another device used to measure low light levels. A PMT is an evacuated tube as shown in the diagram below where photoelectric effect is used to generate photoelectrons which are accelerated by a very high electric field and thus can eject secondary electrons due to impact ionization from electrode surfaces placed along its path as shown in the figure. PMTs are extensively used in fluorescence imaging and similar low light detection applications.



CCD and CMOS Arrays

- So far we talked about single element detectors. For imaging multi-element or arrayed detectors are used. An example is the Charge Coupled Detectors (CCDs) which are used to capture images or record videos. Unlike the photocurrent sensors we talked till now, CCD store photoelectrons as charge stored in a Metal Oxide Semiconductor (MOS) capacitor. By appropriately biasing the metal electrodes, the charges can be read serially from each of the MOS structures forming the array. The array elements are called pixels.

CMOS Imagers

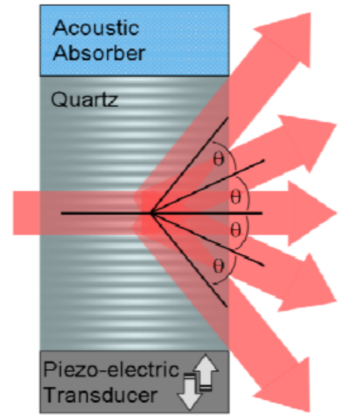
- An alternate image sensors technology which provides faster readout than CCD is called CMOS (Complementary Metal Oxide Semiconductor). These sensors contain active pixels, in the sense that the circuits from converting photocurrents to voltages, amplification etc. are built in with the pixel. CMOS sensors are used in low cost consumer electronic devices such as webcams and mobile phone cameras.

Optical Fibers and Waveguides

- We have seen devices to generate and detect light. There are also devices that can be used to transport light. These are called lightguides or waveguides. Optical fibers are an example of a light guiding device. Light guiding works via total internal reflection which we saw earlier. When a high index region, called the core, is surrounded by a low index region, called cladding, light gets internally reflected in the core according to the ray optics. In the wave optics description we say that the electric field in the cladding region decays exponentially. The light wave then simply follows the path of the high index region. In this manner light signals can be send through a fiber enabling communication links.
- Optical fibers are made from high purity silica (glass). Light is coupled using an optical fiber in biomedical applications such as endoscopy.

Light Modulators

- Light modulators are devices that change (modulate) any parameter associated with a light wave in a controlled, often periodic, manner for e.g. intensity, phase or polarization modulation. Two of the important classes of modulators are Acousto-Optic (AO) modulators shown in the diagram below and Electro-Optic (EO) modulators.
- An AO modulator uses dynamic grating structure formed due to pressure waves in a material to deflect light as shown in the figure. They are used in deflectors and fast scanners in confocal microscopy to be discussed later.



AO Modulators

Image courtesy: Wikipedia Commons

- Electro-optic modulators are devices whose refractive index changes on the application of an electric field. We say earlier that phase retarders (wave-plates) can be used to change polarization states. By using a modulated electrical field, one can use a electro-optic bireferingent material, such as Lithium Niobate, to modulate the phase, polarization and intensity of incident light beam. These devices are called EO modulators.