Monday, April 15, 2013
9:27 AM

LECTURE 43

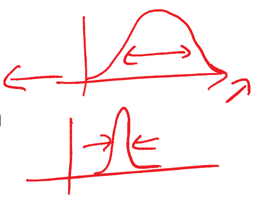
Optoelectronic Devices

EE 121 Part C II

Optoelectronic Devices - the electronic technology in which optical radiation is emitted, modified, or converted (as in electrical-to-optical or optical-to-electrical).

Related technologies:
Photonics - science and technology concerned with the behavior of photons
Electronics - science and technology concerned with the behavior of electrons

Types of devices that are based on semiconductor junction electronics include:
Photodiodes (PDs) – optical radiation is converted to an electrical signal
Light-Emitting Diodes (LEDs) – electrical energy is converted to an optical signal
Laser Diodes (LDs) – electrical energy is converted to optical energy in laser form



Application Examples:
Fiber optic communications
Image processing
Optical sensing

Other Definitions:

Photon - a quantum of electromagnetic energy with no mass, no charge, and energy hc/λ.

Light - electromagnetic radiation in the ultraviolet, visible, and infrared bands or optical range.

Electromagnetic (EM) Spectrum - radiation of all frequencies or wavelengths including electrical power transmission, radio frequencies, optical frequencies, and high-energy rays.

Wavelength λ (in vacuum) or frequency f are related by $\lambda f = c$, where c is the speed of light in vacuum.

Radiation - energy emitted or propagated as waves and energy quanta.

Radiometry – the measurement of radiant EM energy at specific wavelength ranges.

Electromagnetic Energy

The propagation of electromagnetic energy may be characterized by the vacuum wavelength λ, frequency $f = \omega/2\pi$, or quantum energy E_P. These waves travel with a phase velocity of v_P. Material influences can be described by the index of refraction or refractive index n for light propagation.

VACCUM

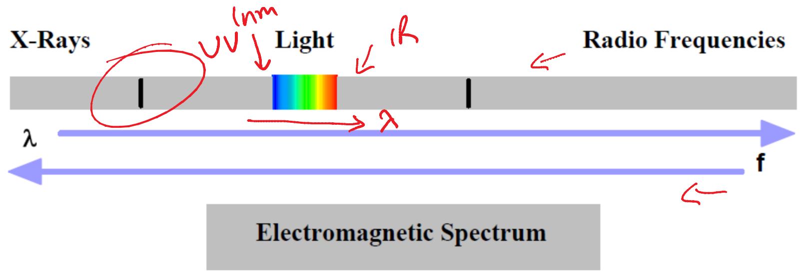
GLASS

The wavelength and frequency are related as
$\lambda f = c$ where c is the speed of light in vacuum.

The quantum energy is
$E_P = hf = hc/\lambda$ where h is Planck's constant.

VACCUM $n=1$

The phase velcity is
$v_p = c/n$ where n is the refractive index (n is unitless and is equal to or greater than 1).



Divisions of the electromagnetic spectrum include the following.

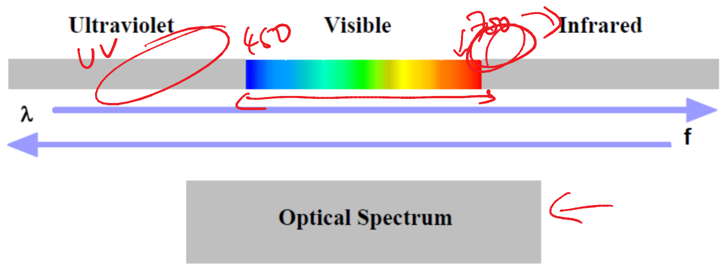
Radio Frequency (RF) - electromagnetic radiation band with frequencies between about 10 kHz and 300,000 Mhz.

Shortwave Spectrum - EM band with wavelengths between about 200 meters and 20 meters; includes the middle bands of radio frequencies.

Microwave Spectrum - EM band with wavelengths between about 1 meters and 1 millimeters; includes the upper bands of radio frequencies.

Light - electromagnetic radiation in the ultraviolet, visible, and infrared bands or optical range with wavelengths between about 1 nm and 105 nm.

X-rays - electromagnetic radiation with wavelengths between about 10 nm and 0.01 nm; usually described as high-energy photons.



Light:
The wavelength λ is associated with color in the visible portion of the spectrum. The effective wavelength inside a material, as well as the phase velocity of light, is then decreased by the refractive index. The effective wavelength and phase velocity are then λ/n and c/n.
Preferred designation for wavelength: vacuum wavelength rather than frequency f or energy.
Preferred designation for semiconductor applications: photon energy E_P
Optical Spectrum: Optical wavelengths extend beyond what the eye can detect and include wavelengths between about 1 nm and 105 nm which interact with materials in similar ways.

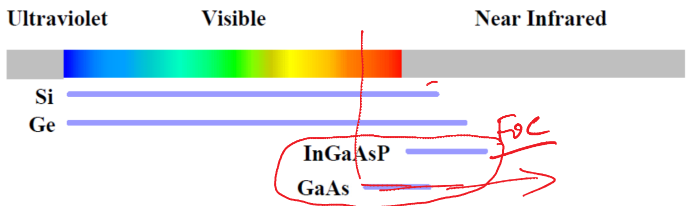
Light Bands	Lower Wavelength Limit	Upper Wavelength Limit
Infrared (IR)	about 700 nm	about 105 nm
Visible	about 450 nm	about 700 nm
Ultraviolet (UV)	about 1 nm	about 450 nm

Wave-Photon Duality: Light displays both wave-like and quantum behavior. Many of the properties of light can be adequately described by waves.
Notable exceptions: emission and absorption.
In particular, photoelectric emission : concept of Photons : quantum mechanics.
Also, the operation of laser diodes and photodiodes can only be explained using a quantum description of semiconductor and light.

The quantum energy $E_P = hf = hc/\lambda$ where h is Planck's constant .

Analysis of Optical Phenomena
Ray Optics - a geometric representation of the behavior of light (also called geometrical optics) which corresponds to the limiting case of $\lambda \to 0$.
Electromagnetic (EM) Optics - or physical optics, an electromagnetic representation of the behavior of light using Maxwell's equations (limiting case as photon number approaches ∞).
Quantum Optics - the most general representation of the behavior of light in terms of photons, i.e. radiant energy packets, using quantum mechanics.

Interaction with Semiconductors
Absorption - loss due to energy conversion as light passes through a material. Photon can be absorbed by electron causing an upward band- to-band transition.
Emission - conversion of energy into light. Photons can be emitted as electrons undergo a downward band-to-band transition.



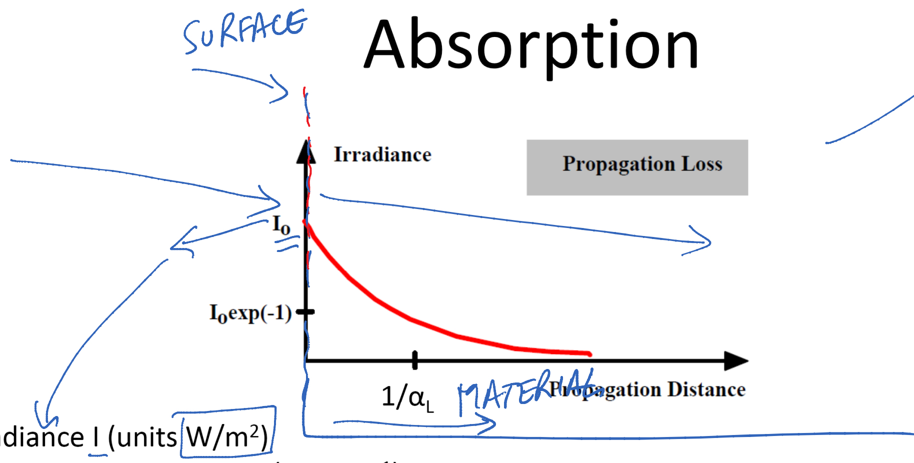
Light Sensitivity of Common Semiconductors

Photodetectors:
Semiconductor structures - Incident photons converted into usable electrons.
Solar cells, CCDs (charge coupled devices), photodiodes, and avalanche photodiodes.
Design of depends on the wavelength sensitivity of the materials.

Detectors made of materials such as InGaAsP are optimized for important optical fiber wavelengths of 1300 nm and 1550 nm.

Semiconductor Sources:
Light Emitting Diodes and Laser Diodes - Light is emitted due to quantum transitions in gases, liquids, or solids. Injection electrolumninescence is the mechanism for light emission in semiconductor diodes. Carriers make a downward transition from the conduction band to the valence band and emit light. Laser sources are characterized by high coherence and directionality over an extremely narrow spectrum.

Absorption



Irradiance I (units W/m^2)
Attenuation constant: α_L (units m^{-1})
The attenuation constant is positive for a lossy media, zero for a lossless media, and negative for a media with gain.

$$I = I_0 e^{(-\alpha_L x)}$$

I_0 is I at x=0

Photodiodes

An optoelectronic device that is based on a semiconductor junction which absorbs light and converts the light input to a current.

- Incident photons are absorbed through upward bandgap transitions VB → CB
- Photon-induced carriers contribute to the drift current (Reverse Bias Operation!) if absorbed within or at the edge of the transition region W.

Photodiode current

$$I = I_0[e^{\frac{qV}{KT}} - 1] - I_{Light}$$

$$I_{Light} = \frac{\eta q P \lambda}{hc}$$ Photon generated current

η = efficiency= carriers generated per incident photon

q = charge per carrier

P = optical power absorbed (J/s)

$\frac{hc}{\lambda}$ =energy per incident photon (J/photon)

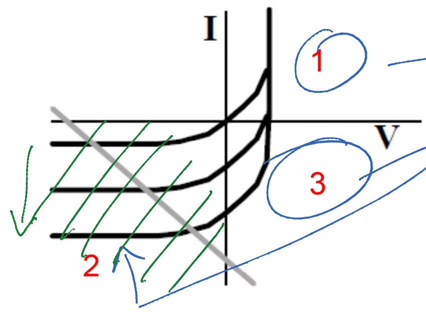
$\frac{P\lambda}{hc}$ =incident photons per second

ALL BUT ONE PARAMETER TO FIND!

Applications:

1) Measuring illumination levels.
2) Convert time varying light signals to electrical signals.

IV curves for photodiode



Regions of Operation:

1) Forward bias
2) Reverse bias: Photodiode
3) Solar cell

Different curves for different I_{Light}

For region 2 and operation away from the knee of the curve:

$I = -I_0 - I_{Light}$

REVERSE SATURATION CURRENT!

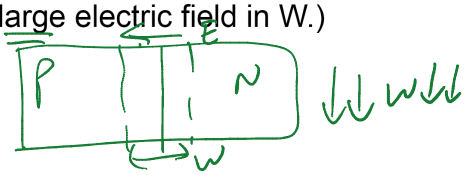
To maximize efficiency:

- Primary absorption in transition region
- Large transition region for large absorption percentage
- Little recombination in transition region (carriers lost to drift current)

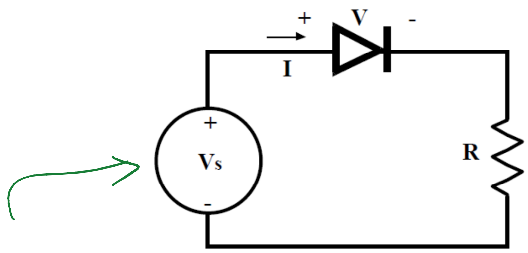
(Note that photo-generated carriers must exit transition region before recombination. Need to have a small recombination lifetime, a small W, and/or a large electric field in W.)

LIGHT → ELECTRONS VB → CB

BACK TO VB X



Photodiode biasing circuit



Note operation in reverse bias: Vs is negative!

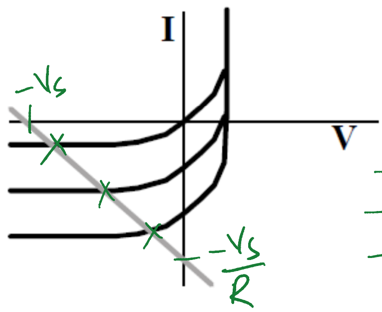
Load Line equation:

V=Vs-IR

For operation away from the knee of the curve:

$I = -I_0 - I_{Light}$

$V = Vs - (-I_0 - I_{Light})R$

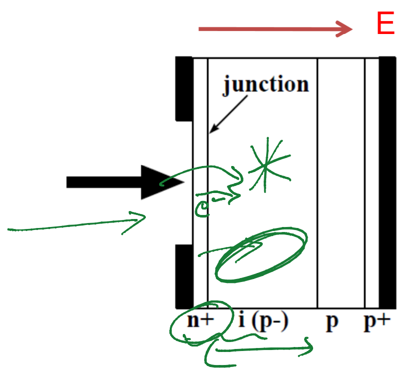


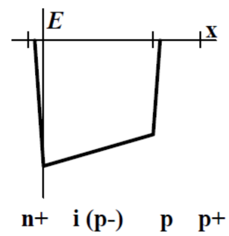
Intercepts for the Load Line:

I=0, V=Vs

V=0, I=Vs/R

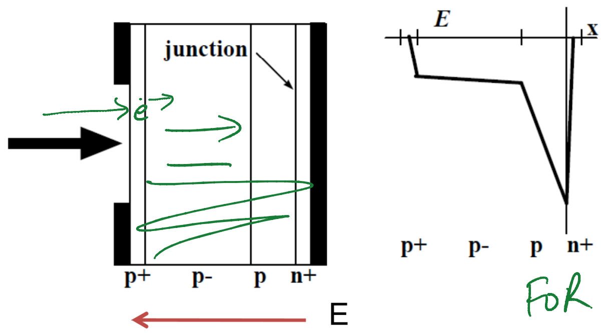
PiN photodiode





- 'i' intrinsic region. Regions p+ and n+ so that most of the depletion region in the intrinsic area.
- Large E field in the 'i' region to help increase the drift current.
- Efficiency $\eta < 1$.
- Thin n+ to allow for light to reach transition region.
- n+ region provides electrons (faster than holes).
- Transition width matched for α_L (absorption rate).

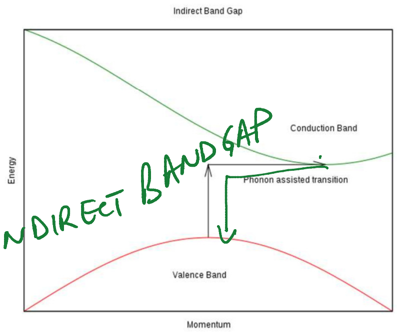
Avalanche Photodiode

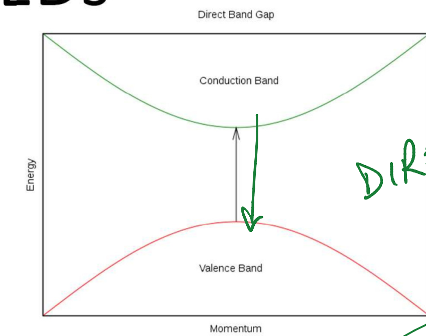


FOR EVERY PHOTON ABSORBED MORE THAN 1 e IS GENERATED!

- 'p-' region for absorption, 'p' region for avalanche multiplication.
- Efficiency η >1.
- Thin p+ to allow for light to reach transition region.
- n+ region provides electrons (faster than holes).
- 'p-' Transition width matched for α_L (absorption rate).

LEDs

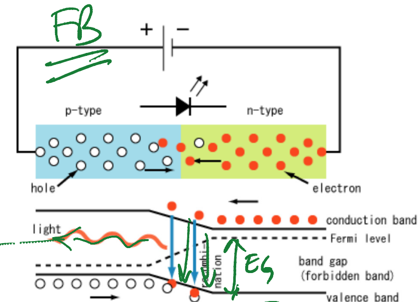




Examples: Si, Ge

Examples: Compound Semiconductors ⇒ GaAs

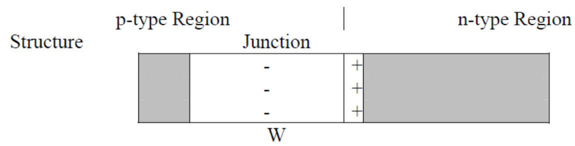
*Conservation of energy and crystal momentum



Note: Images taken from Wikipedia

$E_{g_2} > E_g \rightarrow E_g = \frac{hc}{\lambda}$ → WAVELENGTH OF LIGHT

LED structure



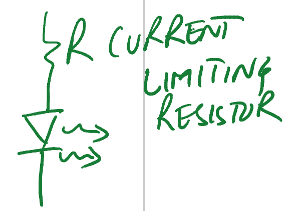
n+p structure

Light Emitting diode (LED): an optoelectronic device that emits non-coherent optical radiation at a photon energy close to bandgap of the junction.

- Structure: Typically a p+n or n+p diode such that the main transitions occur on the n-side or p-side respectively of the depletion region.
- Operation: Forward-bias effect producing spontaneous emission.

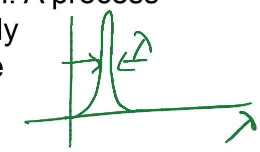
The current is primarily electron flow and the main recombination region is the edge of the depletion region on the p-side.The optical output increases with forward-bias diode current.

An important issue is the re-absorption of emitted photons. Heterostructures (the use of semiconductors with different bandgaps) are often used such that the photons are emitted in a small bandgap semiconductor and exit the diode through a larger bandgap semiconductor.



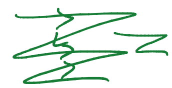
Laser Diode

LASER or Laser: Light Amplification by Stimulated Emission of Radiation. A process that emits optical radiation which is coherent, highly directional, and nearly monochromatic. The spectral purity of laser light is a key property, i.e. the output for a laser has an extremely small spectrum (wavelength spread).



Lasing Operation

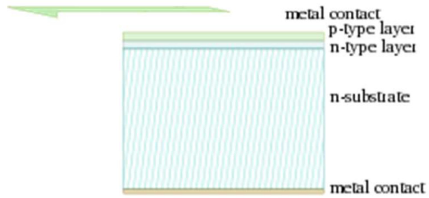
- Active material – A material in which energy is converted into light
- Pumping Mechanism – A mechanism to excite ions, electrons, or molecules so that a light-emitting transition is produced.
- Resonant Cavity – A structure to produce optical feedback, i.e. light is amplified through stimulated emission verses spontaneous emission.

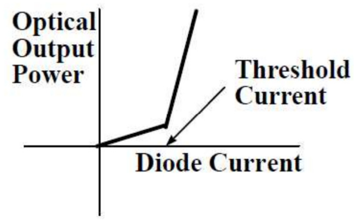


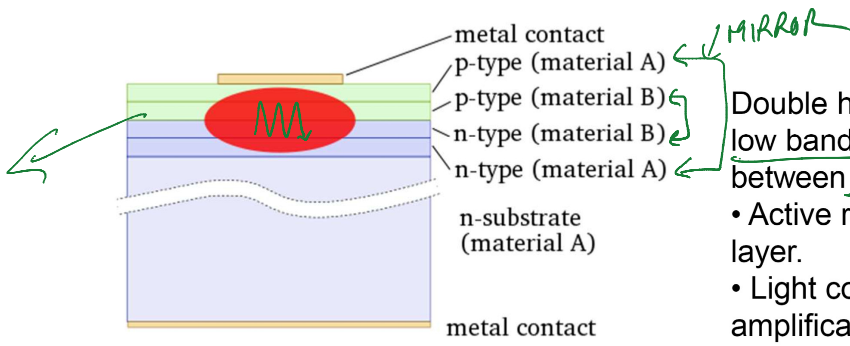
Laser diode (LD): an optoelectronic device that is based on a semiconductor junction which emits optical laser radiation at a photon energy close to bandgap of the junction.

- Active Material – Direct-bandgap Semiconductors
- Pumping Mechanism – Diode Junction Structure (Injection Electroluminescence). Heterostructures are common.
- Resonant Cavity – A Waveguide Structure combined with End-face Mirrors

LASER Diode Structure







Double heterostructure: A layer of low bandgap material sandwiched between two high bandgap layers.

- Active region confined to thin layer.
- Light confinement for amplification purpose

Note: Images taken from Wikipedia