
OPTOELECTRONIC DEVICES

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.

The wavelength and frequency are related as

$$\lambda f = c \text{ where } c \text{ is the speed of light in vacuum.}$$

The quantum energy is

$$E_p = hf = hc/\lambda \text{ where } h \text{ is Planck's constant.}$$

The phase velocity is

$$v_p = c/n \text{ where } n \text{ is the refractive index (} n \text{ is unitless and is equal to or greater than 1).}$$

Divisions of the electromagnetic spectrum include the following.

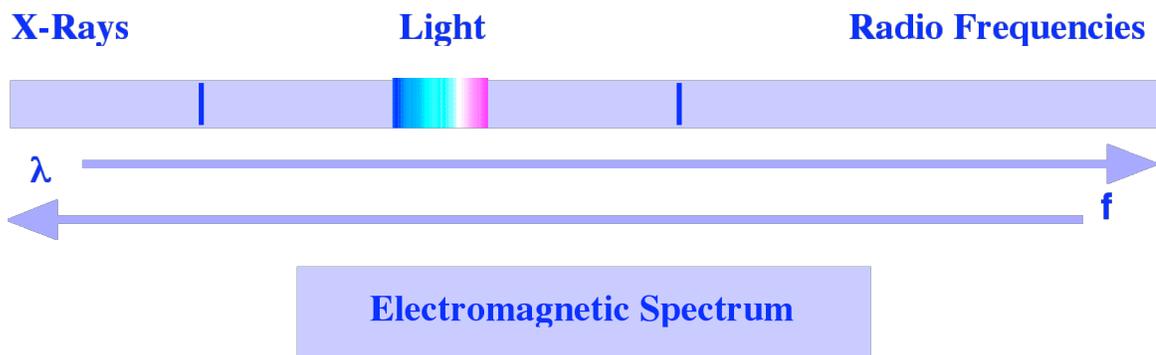
Radio Frequency (RF) - electromagnetic radiation band with frequencies between about 10 kHz and 300,000 Mhz.

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 10^5 nm.

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



OPTICS: THE NATURE OF LIGHT

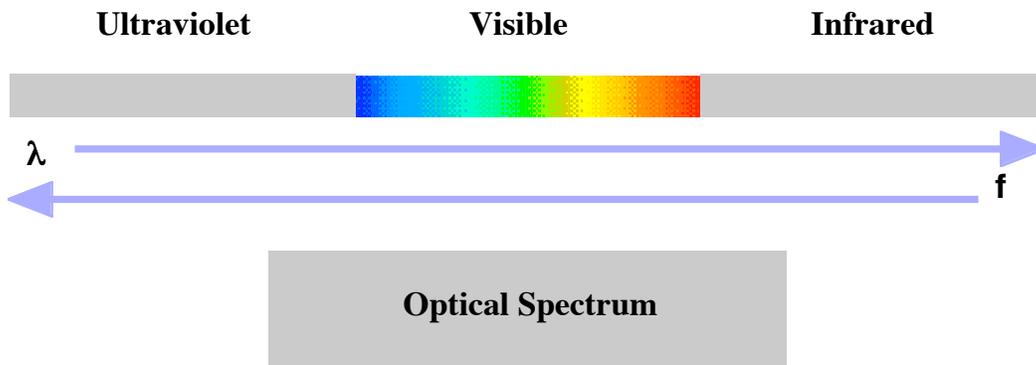
Light refers to radiation in the ultraviolet, visible, and infrared portions of the electromagnetic spectrum. The wavelength λ is associated with color in the visible portion of the spectrum. The effective wavelength inside a material, as well as the phase velocity of light, is then decreased by the 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 10^5 nm which interact with materials in similar ways. For instance, the physical mechanisms behind many optical sources are electronic and molecular transition and the methods of beam control often depend on reflection and refraction from interfaces. Light is subdivided into the ultraviolet, visible, and infrared bands. There are not precise wavelength divisions between bands.

<u>Light Bands</u>	<u>Lower Wavelength Limit</u>	<u>Upper Wavelength Limit</u>
Infrared (IR)	about 700 nm	about 10^5 nm
Visible	about 450 nm	about 700 nm
Ultraviolet (UV)	about 1 nm	about 450 nm



LIGHT ANALYSIS

Wave-Photon Duality: Light is unusual in that it readily displays both wave-like and quantum behavior. Many of the properties of light can be adequately described by waves. Notable exceptions include some cases of emission and absorption. In particular, photoelectric emission led to the concept of photons which was part of the development of the 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. A comparison of the parameters and representations are given.

<u>Wavelengths</u>	<u>Frequency</u>	<u>Quantum Energy</u>
10^5 nm	2.998×10^{12} Hz	1.240×10^{-02} eV
700 nm	4.283×10^{14} Hz	1.771 eV
450 nm	6.662×10^{14} Hz	2.755 eV
1 nm	2.998×10^{17} Hz	1.240×10^3 eV

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 $\lambda \rightarrow 0$.

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

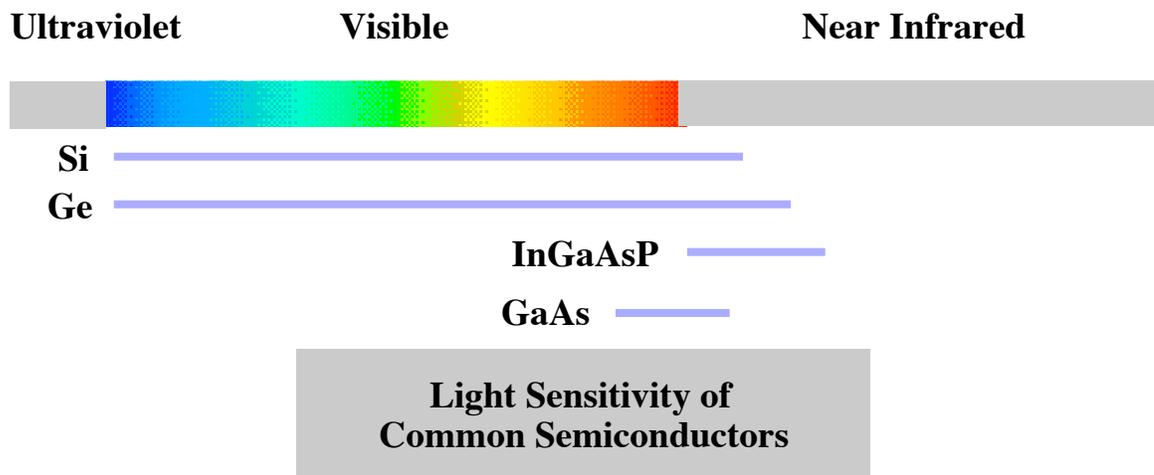
Absorption - loss due to energy conversion as light passes through a material. Photon can be absorbed by electron causing an upward band- to-band transition.

Emission - conversion of energy into light. Photons can be emitted as electrons undergo a downward band-to-band transition.

SEMICONDUCTOR OPTICAL DEVICES

Photodetectors:

Semiconductor structures - Incident photons are converted by semiconductor structures into usable electrons. Solar cells convert light to electrical power. Common devices for imaging and information detection are CCDs (charge coupled devices), photodiodes, and avalanche photodiodes. The design of semiconductor photodetectors depends on the wavelength sensitivity of the materials. For instance, silicon and germanium are sensitive across the visible spectrum and near infrared spectrum. The compound semiconductors InGaAsP and GaAs are sensitive in the upper visible and near infrared. The peak quantum efficiency (electronic conductors generated per incident photon) of about 900 nm in silicon is near its upper cut-off wavelength of 1100 nm. 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 electroluminescence 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.

LIGHT ABSORPTION

Attenuation: A media in which light is propagating may be lossy. For a given wavelength, the irradiance will decrease at a rate proportional to the irradiance magnitude. The resulting loss may be represented by an attenuation constant α_L in units of inverse meter (1/m). The attenuation constant is positive for a lossy media, zero for a lossless media, and negative for a media with gain.

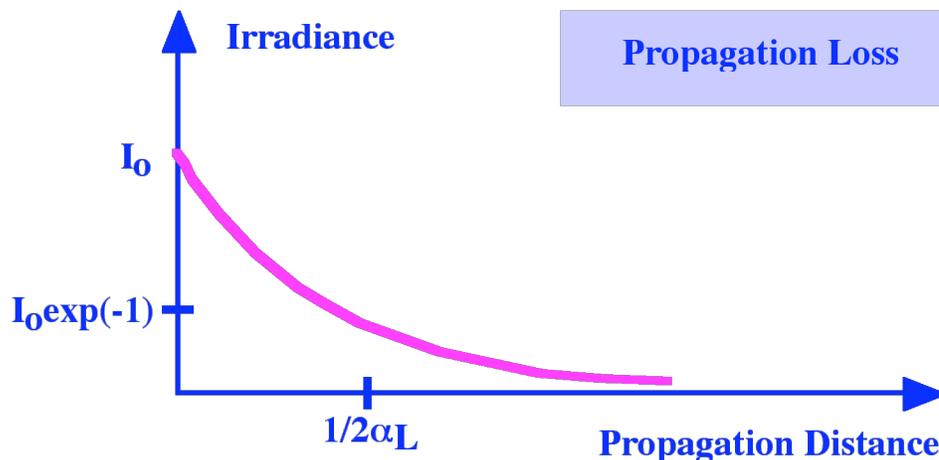
For one-dimension, the defining differential equation for the irradiance (irradiance I with units of W/m^2) amplitude is

$$dI/dx = - \alpha_L I.$$

The solution is

$$I = I_0 \exp(- \alpha_L x)$$

Where I_0 is the value of I at the position ($x=0$).



This loss does not include reflection loss at interfaces.

Care must be taken to distinguish between the exponential loss constant for irradiance and that for fields. The attenuation constant α_L as defined here refers to irradiance. The corresponding exponential loss constant for fields is $\alpha_L/2$. Some texts, especially in the semiconductor field, will define the absorption coefficient (α_L) for irradiance with units of inverse meters (m^{-1}) or inverse centimeters (cm^{-1}) while optics or fields text will use define an equivalent quantity for field attenuation, i.e. equivalent to $\alpha_L/2$. Note that the terminology and symbol notation are sometimes used interchangeably in the literature.

PN PHOTODIODES

Photodiode – 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
- Photon-induced carriers contribute to the drift current if absorbed within or at the edge of the transition region W .

Photodiode current

$$I = I_0 [\exp(qV/kT) - 1] - I_{\text{Light}}$$

Photon-generated current

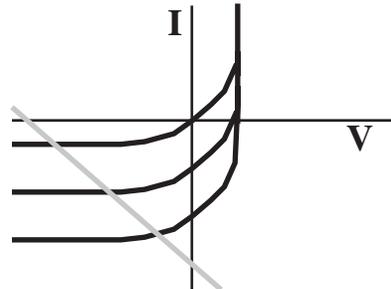
$$I_{\text{Light}} = \eta q P \lambda / hc$$

where η = efficiency = carriers generated per incident photon
 q = charge per carrier
 P = optical power absorbed (J/s)
 hc/λ = energy per incident photon (J/photon)
note: $P\lambda/hc$ = incident photons per second

Photoconductive mode – the current-voltage behavior for reverse bias (negative V) depends on the incident light.

Reverse bias with $V \ll 0$, the current is magnitude is proportional to the optical power with a small offset.

$$I = I_0 [\exp(qV/kT) - 1] - I_{\text{Light}}$$
$$I \sim -I_0 - I_{\text{Light}}$$

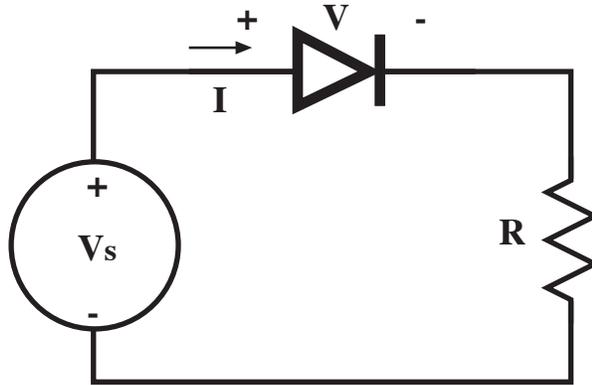


To maximize the efficiency η

- 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 .)

PHOTODIODE BIASING CIRCUIT

The circuit operation of a diode is illustrated in the following figure. Consider a photodiode with a reverse saturation current of $-I_0$.



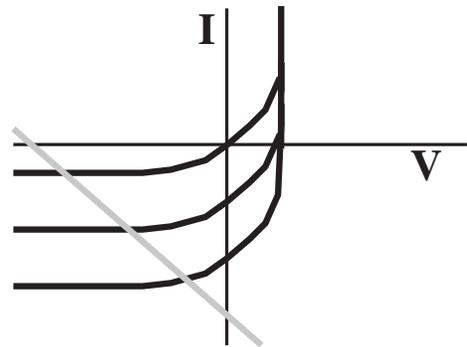
The current is shared by all of the circuit elements. KVL gives the load-line (LL) equation:

$$V = V_S - IR$$

The nonlinear photodiode equation for reverse bias is

$$I = I_0 [\exp(qV/kT) - 1] - I_{\text{Light}}$$

$$I \sim -I_0 - I_{\text{Light}}$$



The load-line equation and the nonlinear diode equation must be satisfied for the operating point simultaneously. The solution depends on the term I_{Light} .

- Reverse Bias (Negative V_S): If the operating V and I are away from the knee of the diode curve, the diode current is approximately

$$I = -I_0 - I_{\text{Light}}$$

and the voltage can be found by substituting I into the LL.

$$V = V_S - (-I_0 - I_{\text{Light}})R$$

Note that the intercepts of the load-line equation are:

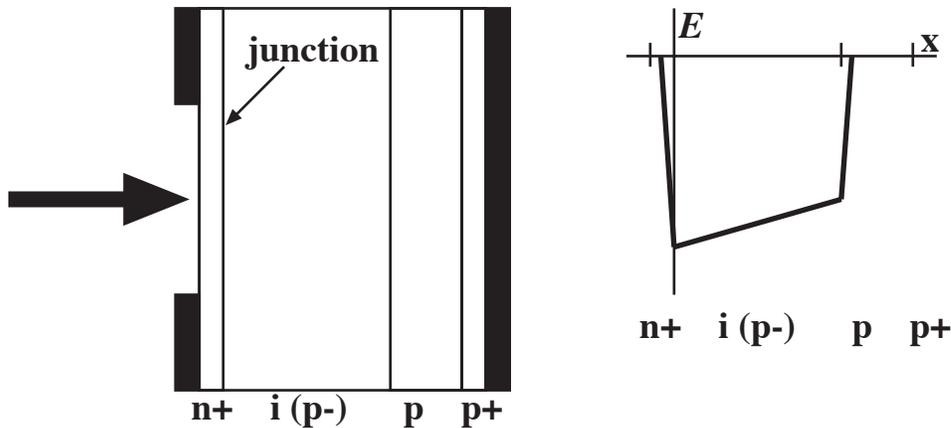
$$I = 0 \text{ for } V = V_S \quad \text{and} \quad V = 0 \text{ for } I = V_S / R$$

PHOTODIODE TYPES – PIN STRUCTURE

PIN or pin Photodiode

- Structure: “i” intrinsic region (commonly p- or n-) between regions with “p” and “n” doping.
- Efficiency: $\eta < 1$

Example Structure



Structural Design and Function

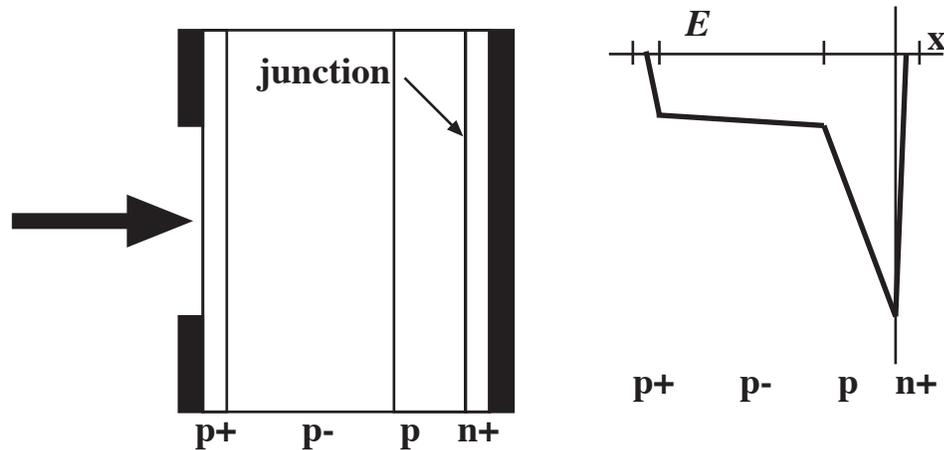
- Thin **n+** region to allow light to reach the transition region
- n+** region provide electrons as the primary carrier (faster than holes)
- Transition region width matched to absorption needs (from α_L)
- Transition region width primarily **i**-region for voltage insensitivity
- Large electric field throughout transition region

PHOTODIODE TYPES – AVALANCHE STRUCTURE

Avalanche Photodiode (APD)

- Structure: “p-” region for absorption and “p” region for avalanche multiplication between regions with “p+” and “n+” doping.
- Efficiency: $\eta > 1$ (one photon gives many carriers by avalanche gain)

Example Structure



Design

- Thin p+ region to allow light to reach the transition region
- n+ region provide electrons as the primary carrier (faster than holes)
- p- transition region width matched to absorption needs (from α_L)
- Separate p multiplication region with large electric field

LIGHT EMITTING DIODES

Emission: A process that converts energy into light.

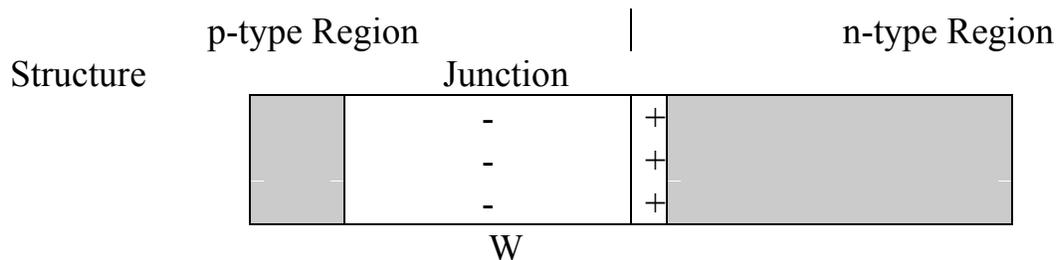
Injection Electroluminescence

- A “direct-bandgap” semiconductor such as GaAs (Si and GE are indirect semiconductors and do not emit light)
- Injected carriers recombine with a light-emitting transition.
- The transition can be spontaneous or stimulated and occurs near the edges of the depletion region in a diode 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.

Example Band Structure for n+p diode (Forward Bias)



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 DIODES

LASER or **Laser**: light amplification by stimulated emission 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).

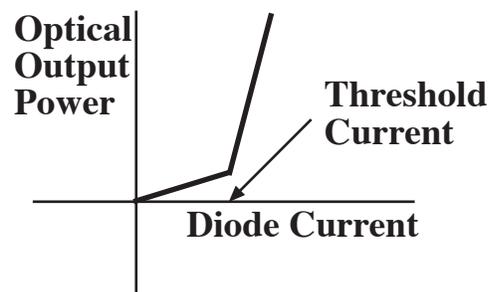
Lasing Operation

- **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

Typical Output Characteristic (Forward Bias)



The **Threshold current** is the diode current needed to produce stimulated emission, i.e. it is the onset of lasing.

A laser diode is highly efficient in that it converts a high fraction of the electrical energy into useful optical output.

EXAMPLES