Optical Detectors

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Week 14

- Course Website: http://courses.washington.edu/me557/optics
- Reading Materials:

  - Week 13 reading materials are from:

  http://courses.washington.edu/me557/readings/
- HW #2 due Week 16
- Set up a schedule to do Lab 2 (those who havne't done the lab, you can do some designs projects relating to LED and detectors and send them to me before 6/25)
- Prism Design Project memo and presentation due next two weeks (here are things you need to send me, video of your oral presentation with demo, PPTs, memos)
- Final Project proposal: Due Today (please follow the instruction on what you need to include in your proposal)
- Final Project Presentation on 6/7 (We will not do the final presentation on 6/7, but instead you will send me the videos of your oral presentations and demos along with your PPTs on 6/8)
- Final project report and all the missing HW's must be turned in by 6/19 5PM
- Please send all these appropriate assignment and project materials to abong@uw.edu according to the due dates.

Again, I need videos of your oral presentations and demos besides your PPTs and reports or memos.

Last week

- Light sources
  - Chemistry 101, orbital model-> energy gap model (light in quantum), spectrum in energy gap
  - Broad band light sources (Orbital energy model, quantum theory, incandescent filament, gas discharge, LED)
  - LED (diode, diode equation, energy gap equation, threshold voltage, device efficiency, junction capacitance, emission pattern, RGB LED, OLED)
  - Narrow band light source (laser, Coherence, lasing principle, population inversion in different lasing medium- ion, molecular and atom gas laser, liquid, solid and semiconductor lasers, laser resonating cavity- monochromatic light, basic laser constitutive parameters)

This Week

- Photodetectors

  - Photoemmissive Cells
  - Semiconductor Photoelectric Transducer
    (diode equation, energy gap equation, reviser bias voltage, quantum efficiency, responsivity, junction capacitance, detector angular response, temperature effect, different detector operating mode, noises in detectors, photoconductive, photovoltaic, photodiode, PIN, APD, PDA, PSD, CCD, CMOS detectors)
  - Thermal detectors (IR and THz detectors)

Types of Optical Detectors

Photon detectors are subdivided according to the physical effect that produces the detector response. We will present some of the important classes of photon detectors as follow:

•***Photoemissive.*** These detectors are based on the photoelectric effect, in which incident photons release electrons from the surface of the detector material. The free electrons are then collected in an external circuit.

Semiconductor

•***Photoconductive***. The incoming light produces free electrons which can carry electrical current so that the electrical conductivity of the detector material changes as a function of the intensity of the incident light. Photoconductive detectors are fabricated from semiconductor materials such as silicon (e.g. photoconductive antenna).

•***Photovoltaic.*** Such a detector contains a junction in a semiconductor material between a region where the conductivity is due to electrons and a region where the conductivity is due to holes (a so-called pn junction). A voltage is generated when optical energy strikes the device (e.g. solar cell).

• **Photodiode:** The current is generated when photons are absorbed in the photodiode. A small amount of current is also produced when no light is present.

•**Thermal detector or IR detector:** A thermal detector absorbs radiation and changes temperature. Because the power in absorbed radiation is typically rather small ($<10^{-7}$ W), the detector itself should be small so that it has a low heat capacity. There are several different kind of detection techniques**: thermoelectric, pyroelectric, bolometer, phnematic**.

Different Photodetectors

1. Photoemissive Cells

There are basically 2 Types of Photo- emissive Cells and these are

- Vacuum Type Photocell

- Gas Filled Type

- Photomultipliers

2. Semiconductor Photoelectric Transducer

These include :

- Photoconductive Cells

- Photovoltaic Cell (solar cell)

- Phototransistors (photodiode, CCD, PIN etc.)

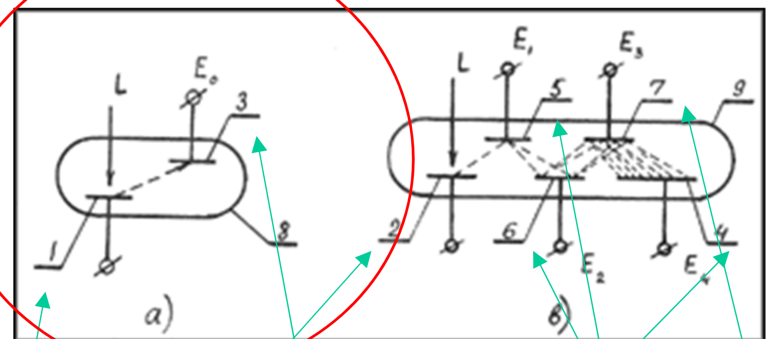
- Photothyristors

3. Thermal detectors (IR detector)

- ***Thermoelectric***
- ***Bolometer***
- ***Pneumatic***
- ***Pyroelectric***
- ***Photoconductive antenna***
- ***GUN, TUNNET, RTD, IMPATT, MIC***

Photoemission Detectors

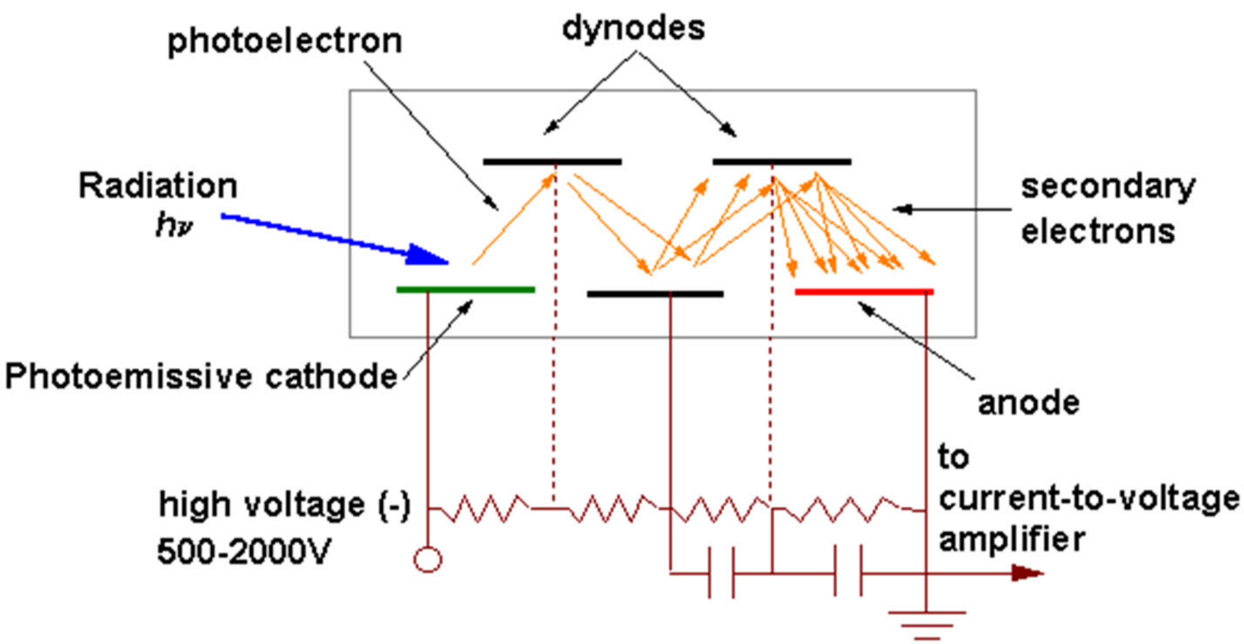
Photoemission detectors are either **evacuated or gas-filled tubes containing a cathode and one or more anodes.** When photons impinge on the cathode, **the electrons are ejected from the cathode surface** and are accelerated toward the anode that is at a positive potential with respect to the cathode. The **photoelectric current increases proportionally to the intensity of the illumination. This design is the simplest diode version of the detector.** In order to increase the sensitivity, several more electrodes (dynodes) are added to the construction of the detector. In this device, called a **photomultiplier,** the electrons that are ejected from the cathode are focused on one of the dynodes. When the surface of the dynode is struck, an **increased number of electrons are liberated.**



(a) Photoemissive cell (b) and photomultiplier. L = light flux, E_o through E_4 = differences in potentials between cathode and one of electrodes, 1 and 2 = cathodes, 3 and 4 = anodes, 5, 6, and 7 = dynodes, 8 and 9 = glass envelopes.

The electrons flow to the next dynode, where the process is repeated with a progressively increasing number of electrons. The dynodes have sequentially higher positive potentials with respect to each other. As a result, the output current has a significantly increased magnitude, which defines the high sensitivity of the detector.

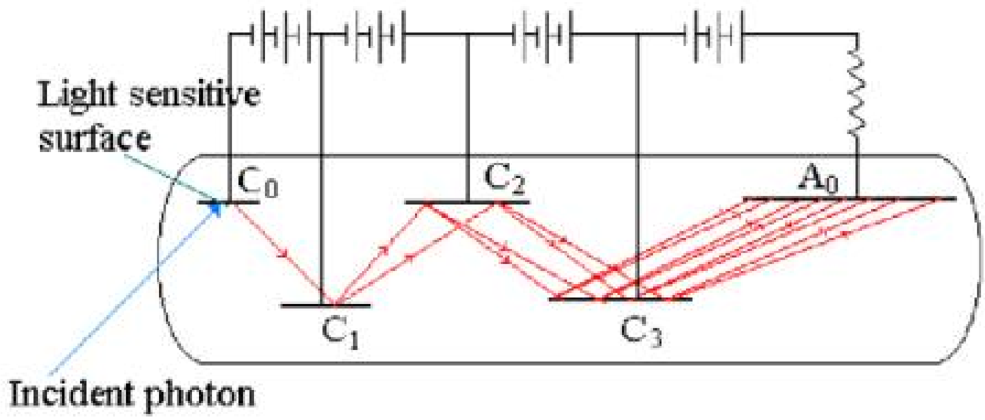
Photomultiplier Tubes (PMTS)



This cascading effect creates 10^5 to 10^7 electrons for each photon hitting the first cathode depending on the number of dynodes and the accelerating voltage. This amplified signal is finally collected at the anode where it can be measured.

Photomultiplier Tubes (PMTS) are light detectors that are useful in low intensity applications such as fluorescence spectroscopy. Due to high internal gain, PMTs are very sensitive detectors.

Photomultiplier Tubes

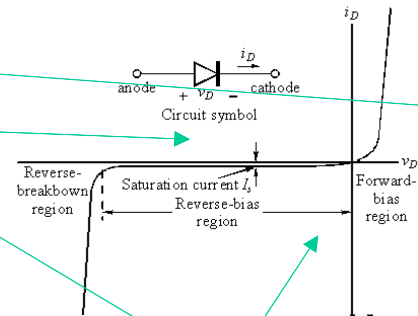


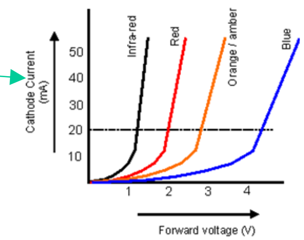
Secondary emission of electrons due to high velocity electrons
- Amplification is very high (10,000x possible)
- Used in single photon counter

Mim Lal Nakarmi, KSU

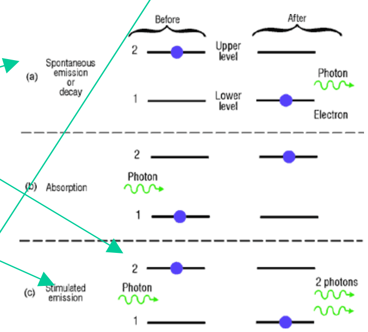
Why Semiconducting Materials?

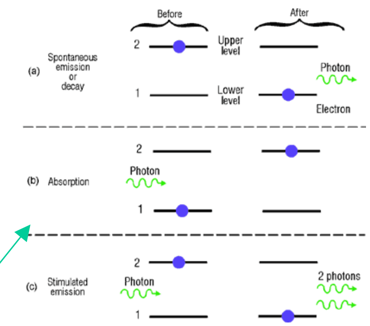
Rectification and control electrical current with charges and also longer life time





- On/off switching (e.g. passing current more easily in one direction than the other, retification) (diode)
- Current or voltage driven amplification (diode)
- Energy converter (solar cell, photo detector etc.)
- Nonlinear IV characteristic (diode)
- Easily doped or change layer structure to change electromagnetic properties (mu, epsilon etc.) to create variable resistance, capacitance and its sensitivity to light or heat (e.g. different wavelengths)





Semiconductor

Variable conductivity

A pure semiconductor is a poor electrical conductor as a consequence of having just the right number of electrons to completely fill its **valence bonds**. Through various techniques (e.g., **doping or gating**), the semiconductor can be modified to have excess of electrons (becoming an ***n*-type semiconductor**) or a deficiency of electrons (becoming a ***p*-type semiconductor**). In both cases, the semiconductor becomes much more conductive (the conductivity can be increased by a factor of one million, or even more). Semiconductor devices exploit this effect to shape electrical current.

Junctions

When doped semiconductors are joined to metals, to different semiconductors, and to the same semiconductor with different doping, the resulting junction often strips the electron excess or deficiency out from the semiconductor near the junction. This depletion region is rectifying (only allowing current to flow in one direction), and used to further shape electrical currents in semiconductor devices.

Energetic electrons travel far

Electrons can be excited across the energy band gap of a semiconductor by various means. These electrons can carry their excess energy over distance scales of microns before dissipating their energy into heat, significantly longer than is possible in metals. This effect is essential to the operation of bipolar junction transistors.

Light energy conversion

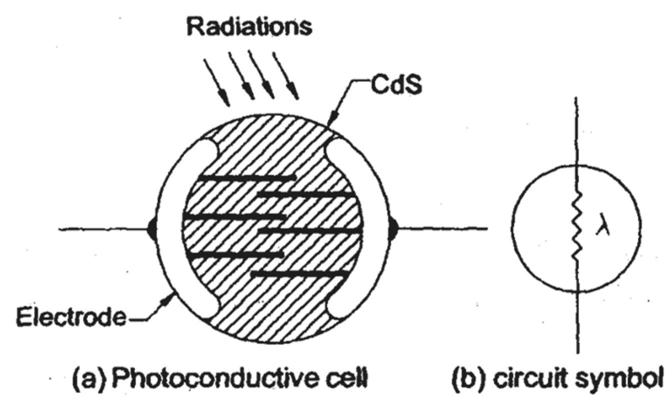
Electrons in a semiconductor can absorb light, and subsequently retain the energy from the light for a long enough time to be useful for producing electrical work instead of heat. This principle is used in the photovoltaic cell (e.g. solar cell). Conversely, in certain semiconductors, electrically excited electrons can relax by emitting light instead of producing heat. This is used in the light emitting diode.

Thermal energy conversion

Semiconductors are good materials for thermoelectric coolers and thermoelectric generators, which convert temperature differences into electrical power and vice versa. Peltier coolers use semiconductors for this reason.

Photoconductive Materials

The four materials normally employed in photoconductive devices are: Cadmium Sulphide (CdS), Cadmium Selenide (CdSe), lead sulphide (PbS) and Thallium Sulphide (TlSIn) a typical construction of photoconductive device, **thin film is deposited on an insulating substrate**. **The electrodes are formed by evaporating metal such as gold through a mask to give comb -like pattern as shown.** The geometry results in a relatively large area of sensitive surface and a small inter electrode spacing. This helps the device to provide high sensitivity.



Geometry of the photoconductive cell

Photoconductive Materials

Desired characteristics of photoconductive materials

i) High spectral sensitivity in the wavelength region of interest
ii) Higher quantum efficiency
iii) Higher photoconductive gain
iv) Higher speed of response and
v) lesser noise

Photoconductive Materials

(i) Cadmium sulfide (CdS) and Cadmium selenide (CdSe)

These are highly sensitive in the visible region of radiation.They have high photoconductive gains (10^3 to 10^4) but poor response time (about 50 ms). The response gets reduced at higher illumination levels indicating the presence of traps.

(ii) Lead sulfide (PbS)

It has spectral responsivity from 1 to 3.4 μm and hence very much suitable for fabricating near-infrared detectors. It has maximum sensitivity in the region of 2 μm with typical response time about 200 μs.

(iii) Indium antimonide (InSb)

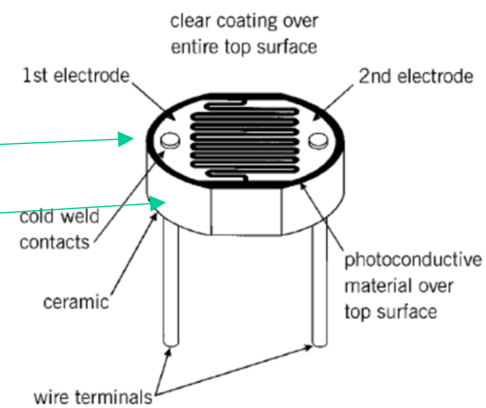
These detectors have wavelength response extending out to 7 μm and exhibit response times of around 50 ns.

(iv) Mercury cadmium telluride (HgxCd1-x Te)

This is an alloy composed of the semi-metal HgTe and the semi-conductor CdTe. Semi-metals have overlapping valence and conduction bands. Depending on the composition of alloy, a semiconductor can be formed with a bandgap varying between zero and 1.6eV. Correspondingly the detector sensitivities lie in the range 5 to 14 μm. Photoconductive gains of up to 500 are possible.

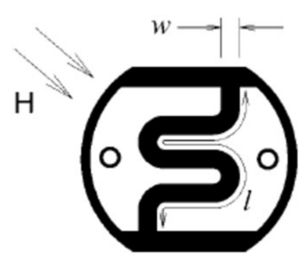
Photoconductive Cell

Photocells are high resistance thin film devices made by depositing a layer of a photoconductive material on a ceramic substrate.



For a given type of photoconductor material, at a given level of illumination, the photoconductive film will; have a certain sheet resistivity. The resistance of the photocell at this light level is determined by the electrode geometry: $\boxed{R_H = \rho_H(\frac{w}{l})}$

where:



R_H = resistance of cell at light level H

ρ_H = sheet resistivity of photoconductive film at light level H

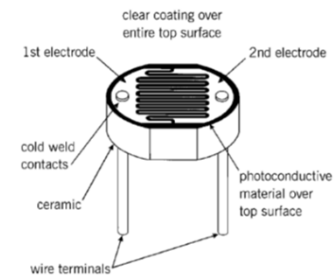
w = width of electrode gap

l = length of electrode gap

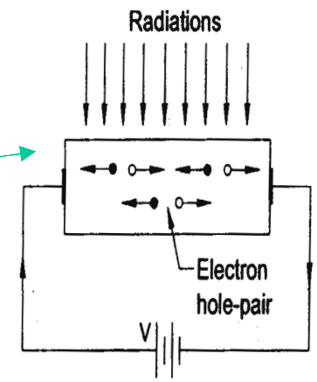
Sheet sensitivity (ρ_H) for photoconductive films at 2 fc are in the range of 20 MΩ per square.

The ratio w / l can be varied over a wide range in order to achieve design goals. Typical values for w / l run from 0.002 to 0.5, providing flexibility for terminal resistance and maximum cell voltage.

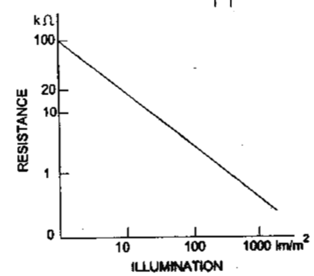
Photoconductive Cells

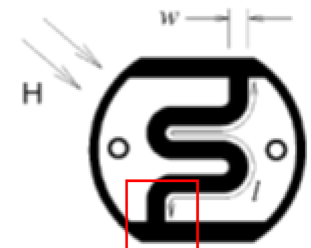


In these semiconductor based detectors light whose energy is greater than that of the bandgap causes the generation of electron-hole pairs. As long as the electron remains in the conduction band, the conductivity of the semiconductor will be increased. This is the phenomenon of photoconductivity, which is the basic mechanism operative in photoconductive detectors.



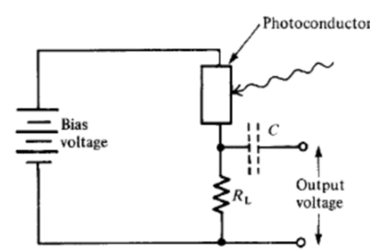
The bulk effect photoconductors have **no junction.** The bulk **resistivity decreases with increasing illumination**, allowing more photocurrent to flow. This resistive characteristic gives bulk effect photoconductors a unique quality: signal current from the detector can be varied over a wide range by adjusting the applied voltage.



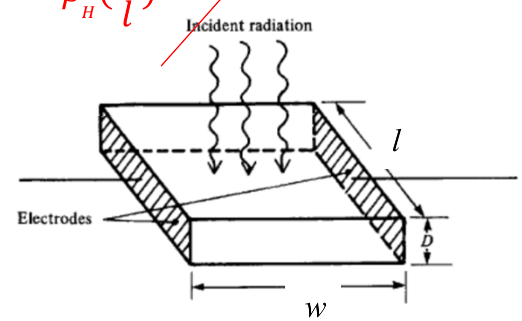


$$\rho_H = 1/\delta_H$$

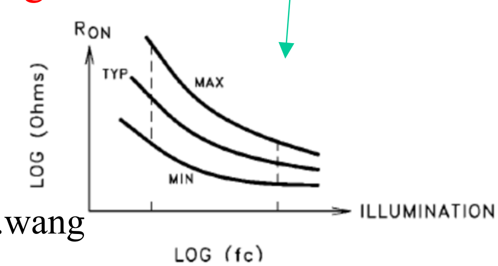
$$R_H = \rho_H \left(\frac{w}{l}\right)$$



Photoconductor bias circuit: changes in the resistance of the photoconductor cause changes in the voltage appearing across R_L.



Geometry of a slab of photoconductive material. The slab of length L, width W and thickness D has electrodes on opposite faces; radiation falls onto the upper face.



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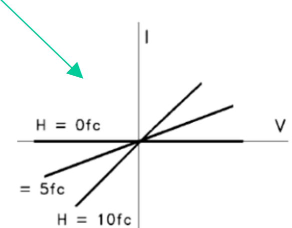


fc= photocurrent

Photoconductive Cell

Let us consider a photoconducting slab. It is simply a light sensitive semiconductor material with ohmic contacts on both ends.

When the material is illuminated with photons of energy $E \geq E_g$

electron hole pairs are generated and the electrical conductivity of the material increases, where Eg is the bandgap energy of the semiconductor material given by

$$E_g = \frac{hc}{\lambda}$$

Where λ is the wavelength of the incident photon .

Photoconductive Cell

Let I_0 be the intensity of monochromatic light falling normally onto the slab. Then the intensity of transmitted light I is given by

$$I = I_0 \, e^{-\alpha D}$$

Where α is the absorption coefficient of the material and D is the thickness of the slab.

ABSORPTION

Recall

When a large group of atoms is assembled and irradiated with light, most of those atoms are in the ground-state energy level. If the photons of the impinging light have the appropriate energy ΔE_{20} for example, the light will be absorbed according to the following expression for the variation of intensity I with the distance L into the material (known as (**Lambert Law**):

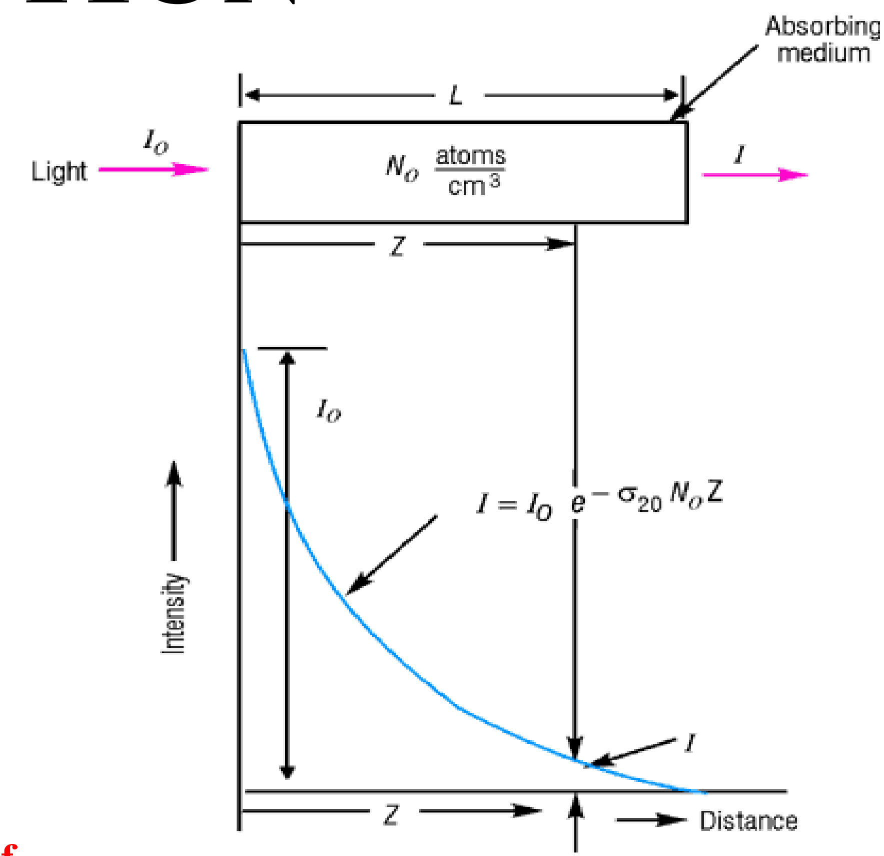
$$I = I_0 e^{-\sigma_{20} N_0 L}$$

Where I_0 = **intensity of the beam when it first reaches the atoms**

σ_{20} = **cross section for absorption or emission of those two levels (cm^2),**

N_0 = **population density of atoms residing in level 0 (atoms/cm^3),**

$\sigma_{20} N_0$ = **absorption coefficient**



A. Guenther UCONN

Intensity variation versus depth z into an absorbing sample

Photoconductive Cell

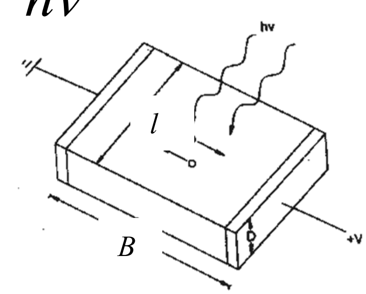
Let L and B (same as W in earlier page) be the length and breadth (width) of the photoconductive slab respectively. Also let us assume that the slab absorbs the entire light falling on it. Then the light energy falls on the sample per sec is given by

$$\boxed{I_0 BL}$$

where I_0 is the light energy falling per second on unit area of the slab. Therefore the number of photons falling on the photoconductor per second $= \dfrac{I_0 BL}{h\nu}$ remember $E_g = \dfrac{hc}{\lambda}$

Let η- be the quantum efficiency of the absorption process. It is nothing but the fraction of incident energy absorbed.

Therefore the number of electrons (holes) collected as Ip/sec $= \eta \dfrac{I_0 BL}{h\nu}$



Now the average generation rate of charge carriers is given by

Generation rate in terms of photon absorption

$$r_g = \frac{\eta I_0 BL}{h\nu BLD} \Rightarrow \boxed{r_g = \frac{\eta I_0}{h\nu D}}$$

Quantum efficiency

How well energy covert

A photodiode's capability to convert light energy to electrical energy, expressed as a percentage, is its Quantum Efficiency, (Q.E.).

$$\eta = r_e/r_p = \frac{\text{\# of electrons (holes) collected as } I_p\text{/sec}}{\text{\# of incident photons/sec}}$$

Depends on λ, through absorption coefficient, thickness of layers, Doping, geometry, etc. Operating under ideal conditions of reflectance, crystal structure and internal resistance, a high quality silicon photodiode of optimum design would be capable of approaching a Q.E. of 80%.

Photoconductive Cell

Let Δn and Δ p be the excess electron and hole density per unit volume in the device. If τ_c is the life time of charge carriers, then the recombination rate

$$\boxed{r_r = \frac{\Delta n}{\tau_c} = \frac{\Delta p}{\tau_c}}$$

At equilibrium, the recombination rate = generation rate

Therefore $\boxed{\Delta p = \Delta n = r_r \tau_c = r_g \tau_c}$

We know the conductivity of a semiconducting material is

$$\boxed{\sigma = ne\mu_e + p.e\mu_h}$$

Under illumination the conductivity will increase by an amount is

$$\boxed{\begin{aligned} \Delta\sigma &= \Delta n e\mu_e + \Delta p.e\mu_h \\ &= \Delta n e(\mu_e + \mu_h) \\ &= r_g \tau_c e(\mu_e + \mu_h) \end{aligned}}$$

Conductivity in terms of generation rate

μ_e and μ_h are electron and hole mobility

Photoconductive Cell

The ratio B/L can be varied over a wide range in order to achieve design goals. Typical values for B/L run from 0.002 to 0.5, providing flexibility for terminal resistance and maximum cell voltage.

When a voltage is applied to the contacts, electrons and holes move in opposite directions resulting in a photocurrent give

Ohm's law i= V/R

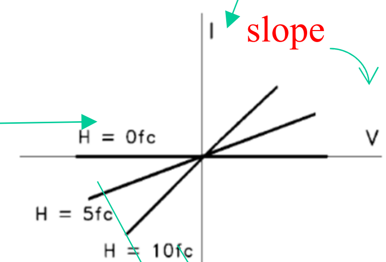
$$\boxed{\Delta i = \frac{BD}{L}\Delta\sigma V}$$

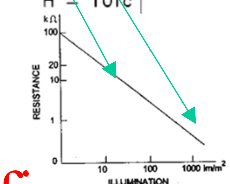
$$\Delta\sigma = \Delta ne\,\mu_e + \Delta p.e\,\mu_h$$
$$= \Delta ne(\mu_e + \mu_h)$$
$$= r_g\,\tau_c e(\mu_e + \mu_h)$$

$$\boxed{\Delta i = \frac{BD}{L} r_g \tau_c e(\mu_e + \mu_h)V}$$

$$r_g = \frac{\eta I_0}{h\nu D}$$

slope





The quantum efficiency of a photoconductor device is defined by the term photoconductor gain G. Photoconductive gain is defined as the ratio of rate of flow of electrons per second to the rate of generation of electron hole pairs within the device.

$$G = \frac{Rate\,of\ flow\,of\ electrons/\sec}{Rate\,of\ generation\,of\ electron-hole\,pairs} \quad \Rightarrow \quad G = \frac{(\Delta i/e)}{r_g BLD}$$

Where rate of flow of electrons per sec=$\Delta i/e$ and Rate of generation of electron hole pairs = $r_g BLD$

Photoconductive Cell

Since photoconductive gain is defined as:

$$\Delta i = \frac{BD}{L} r_g \tau_c e(\mu_e + \mu_h)V$$

$$G = \frac{Rate\ of\ flow\ of\ electrons\ /\ sec}{Rate\ of\ generation\ of\ electron - hole\ pairs} \Rightarrow G = \frac{(\Delta i / e)}{r_g\ BLD}$$

$$r_g = \frac{\eta I_0}{h\nu D}$$

The **photoconductive gain G** can be increased by increasing the voltage V and decreasing the length, L of the device.

$$\Rightarrow \boxed{G = \frac{\tau_c(\mu_e + \mu_h)V}{L^2}}$$

How efficient all recombination turns into current conduction

The photoconductive gain can also be defined as the ratio of the minority carriers life time τ_c and the transit time t.

$$G = \frac{\tau_c}{t}$$

Why Use Photocells?

- *Lowest cost available in visible and near-IR photo detector*
- *Available in low cost plastic encapsulated packages as well as hermetic packages (TO-46, TO-5, TO-8)*
- *Responsive to both very low light levels (moonlight) and to very high light levels (direct sunlight)*
- *Wide dynamic range: resistance changes of several orders of magnitude between "light" and "no light"*
- *Low noise distortion*
- *Maximum operating voltages of 50 to 400 volts are suitable for operation on 120/240 VAC*
- *Available in center tap dual cell configurations as well as specially selected resistance ranges for special applications*
- *Easy to use in DC or AC circuits - they are a light variable resistor and hence symmetrical with respect to AC waveforms*
- *Usable with almost any visible or near infrared light source such as LEDS; neon; fluorescent, incandescent bulbs, lasers; flame sources; sunlight; etc*
- *Available in a wide range of resistance values*

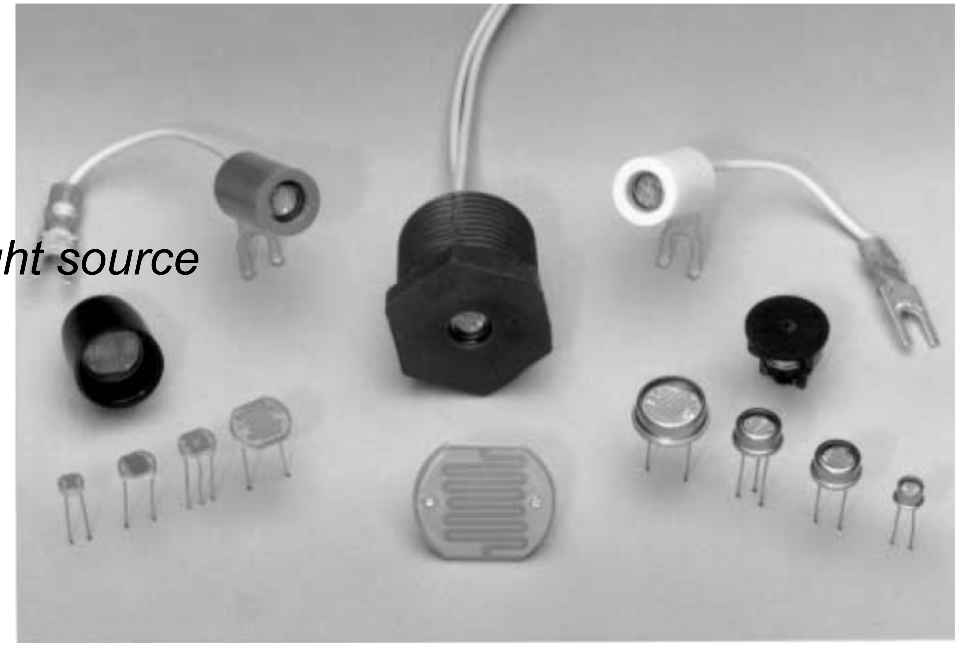
Applications

Photoconductive cells are used in many different types of circuits and applications.

Analog Applications

- *Camera Exposure Control*
- *Auto Slide Focus - dual cell*
- *Photocopy Machines - density of toner*
- *Colorimetric Test Equipment*
- *Densitometer*
- *Electronic Scales - dual cell*
- *Automatic Gain Control - modulated light source*
- *Automated Rear View Mirror*

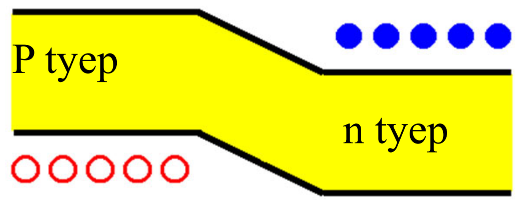
** Detecting ship and aricraft*



Digital Applications

- *Automatic Headlight Dimmer*
- *Night Light Control*
- *Oil Burner Flame Out*
- *Street Light Control*
- *Absence / Presence (beam breaker)*
- *Position Sensor*

Semiconductor PN Junction types

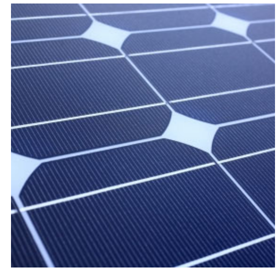


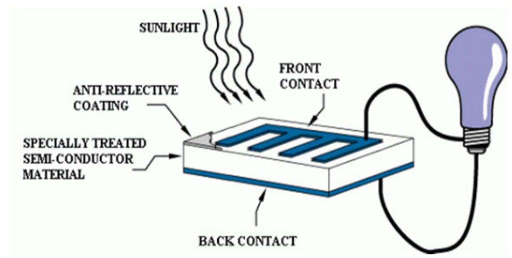
P-N junction (no bias, short circuit)

1. Absorbed hν excited e from valence to conduction, resulting in the creation of e-h pair
2. Under the influence of a bias voltage these carriers move through the material and induce a current in the external circuit.
3. For each electron-hole pair created, the result is an electron flowing in the circuit.

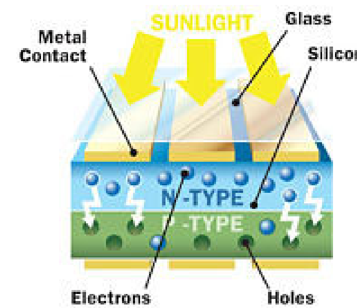
Photovoltaic Cell

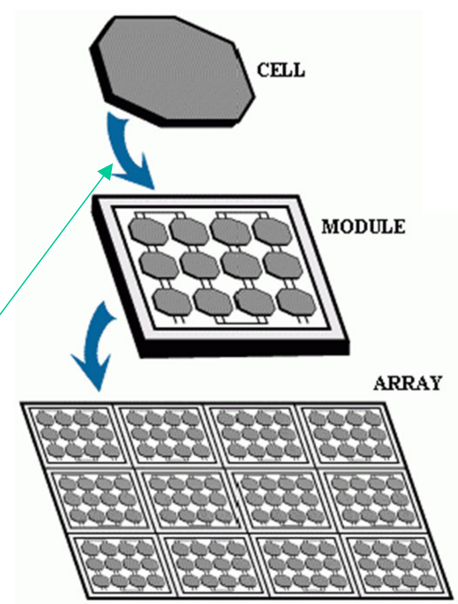
All photovoltaic (PV) cells consist of two or more thin layers of semi-conducting material, most commonly silicon (monocrystalline, polycrystalline, amorphous, thick film) and other materials such as cadmium telluride (CdTe) and copper indium diselenide (CIS).

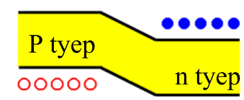




Thee semiconductor wafers are specially treated to form an electric field, positive on one side and negative on the other. When light energy strikes these cells, electrons are knocked loose from the atoms in the semiconductor material. If electrical conductors are attached to the positive and negative sides, forming an electrical circuit, the electrons can be captured in the form of an electric current The electrical output from a single cell is small, so multiple cells are connected together to form a 'string', which produces a direct current.







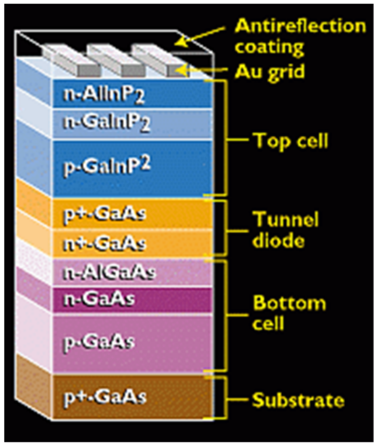
Multi-junction Cell

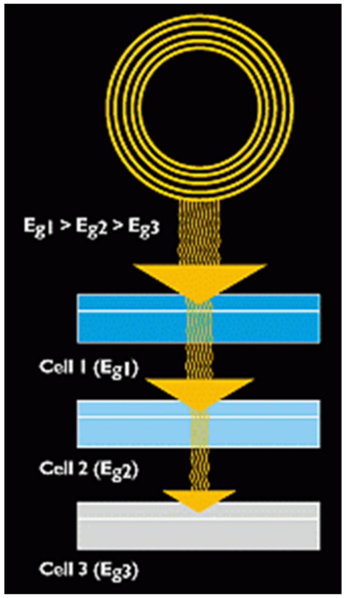
Today's most common PV devices use a single junction, or interface, to create an electric field within a semiconductor such as a PV cell. In a single-junction PV cell, only photons whose energy is equal to or greater than the band gap of the cell material can free an electron for an electric circuit.

One way to get around this limitation is to use two (or more) different cells, with more than one band gap and more than one junction, to generate a voltage. These are referred to as "multijunction" cells (also called "cascade" or "tandem" cells). Multijunction devices can achieve a higher total conversion efficiency because they can convert more of the energy spectrum of light to electricity.

Much of today's research in multijunction cells focuses on gallium arsenide as one (or all) of the component cells. **Such cells have reached efficiencies of around 35% under concentrated sunlight (compare to 15% monocrystal silicon).** Other materials studied for multijunction devices have been **amorphous silicon and copper indium diselenide (CIS). .**

As shown below, a multijunction device is a stack of individual single-junction cells in descending order of band gap (E_g). The **top cell captures the high-energy photons and passes the rest of the photons on to be absorbed by lower-band-gap cells.**

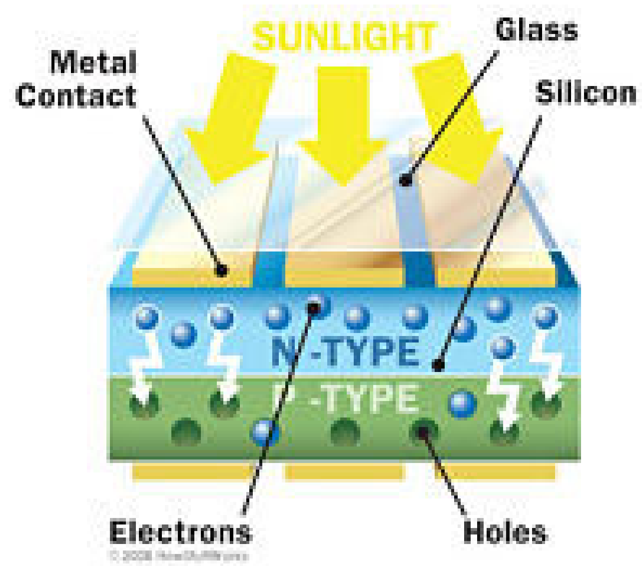


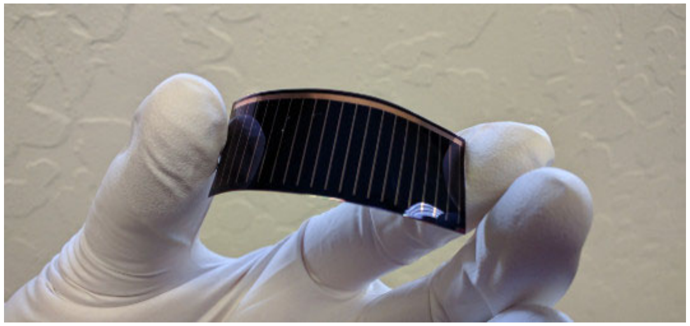


Photovoltaic Cell

(Organic Solar Cell)

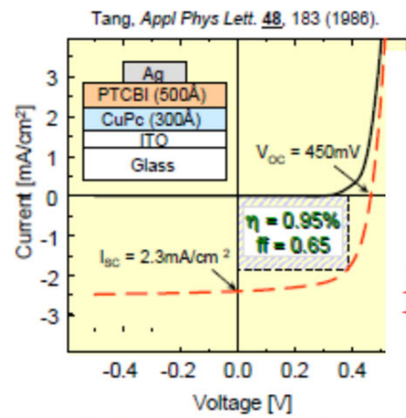
Organic thin-film solar cells using low-molecular-weight materials are fabricated by vacuum deposition. First, organic materials having p- and n-type conductivities are successively deposited on a transparent electrode, and then, a metal electrode is deposited on them. The mechanism of electrical power generation in OSCs can be understood as an opposite process of emissions in OLEDs. Sunlight is absorbed by organic layers in OSC, and excitons generated by light absorption are dissociated to electrons and holes at the interface between p- and n-type organic layers. **The electrons and holes are collected at the upper and lower electrodes, respectively, and electricity is generated.** Furthermore, it is known that power conversion efficiency is improved by insertion of an electron transport layer.

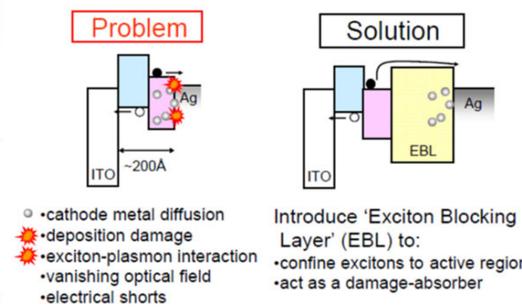




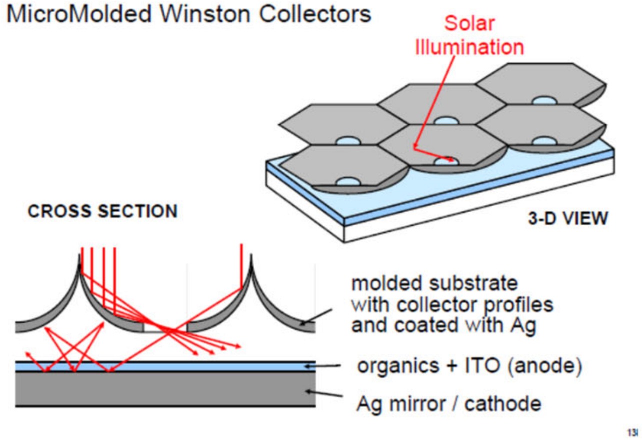
Solar cell

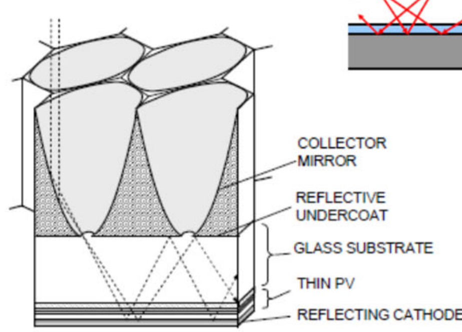
- Heterojunction to improve coupling efficiency
- Multilayer for broadband
- Lenses, mirror arrays to improve light collection





MicroMolded Winston Collectors





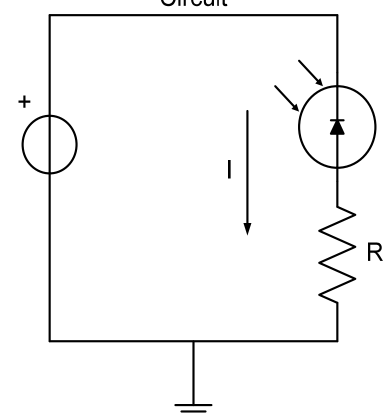
Peumans et al, US Patents #6440, 769, Aug 27, 2002

Photodiodes and Phototransistors

– Photodiodes are designed to detect photons and can be used in circuits to sense light.

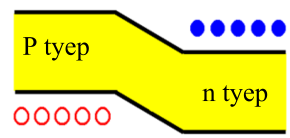
– Phototransistors are photodiodes with some internal amplification.

Photodiode Light-detector Circuit

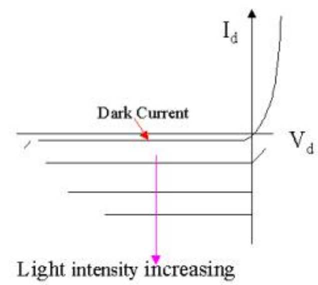


<u>Note</u>:

Reverse current flows through the photodiode when it is sensing light.

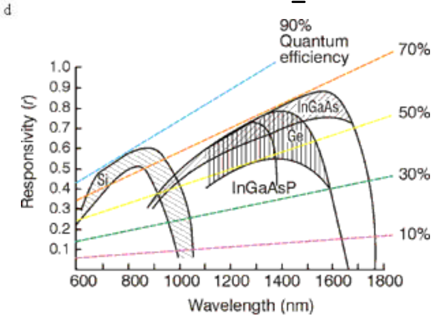


If photons excite carriers in a reverse-biased pn junction, a very small current proportional to the light intensity flows.



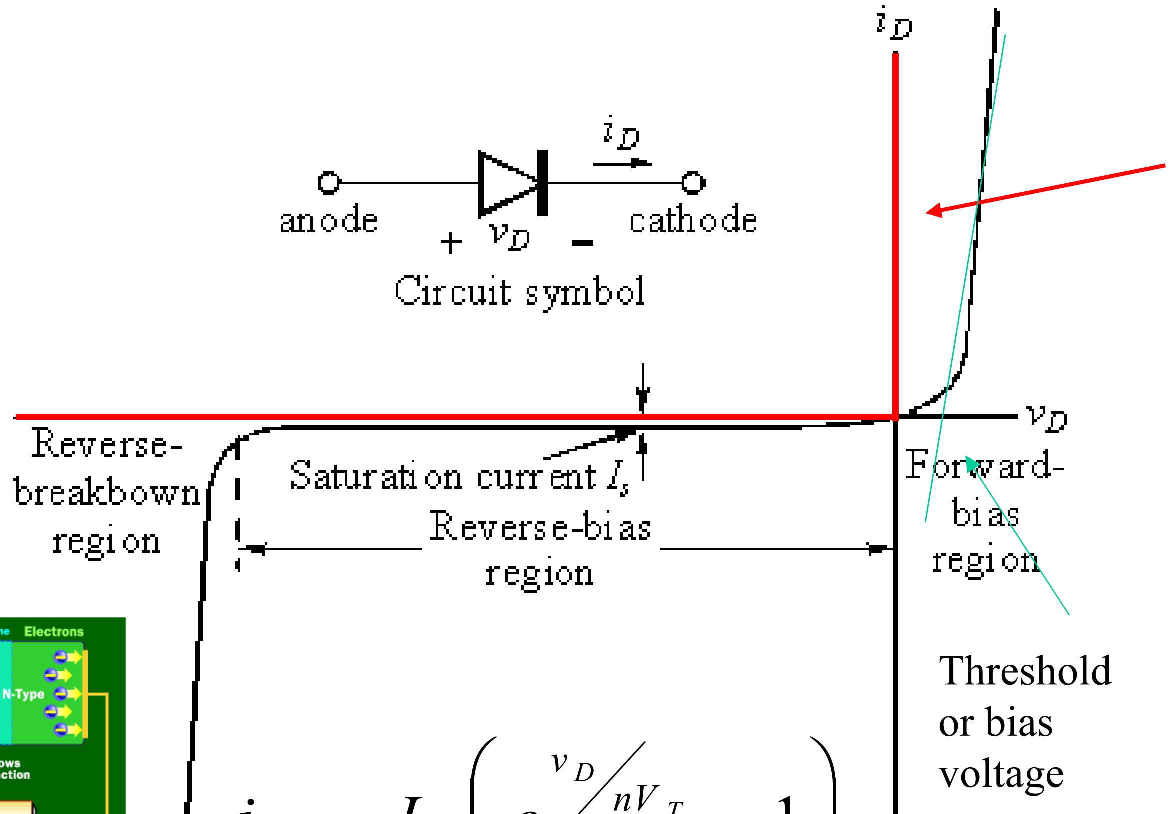
Reverse bias characteristic

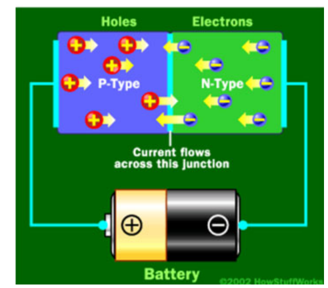
The sensitivity depends on the wavelength of light.

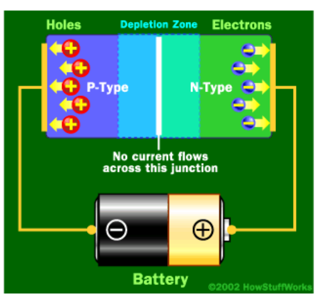


i-v characteristic of a real diode

- Real diode is close to ideal







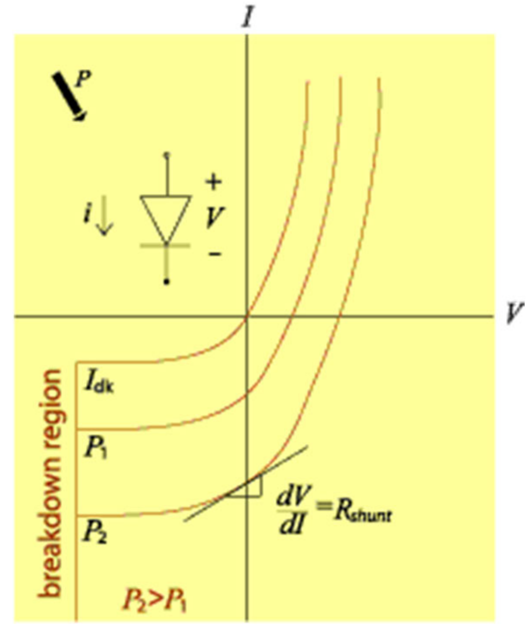
$$i_D = I_S \left(e^{v_D / nV_T} - 1 \right)$$

Photodiode Operation

A photodiode behaves as a photocontrolled current source in parallel with a semiconductor diode and is governed by the standard diode equation

$$I_d = I_{do}\left(e^{qV_d/2kT} - 1\right) + I_p$$

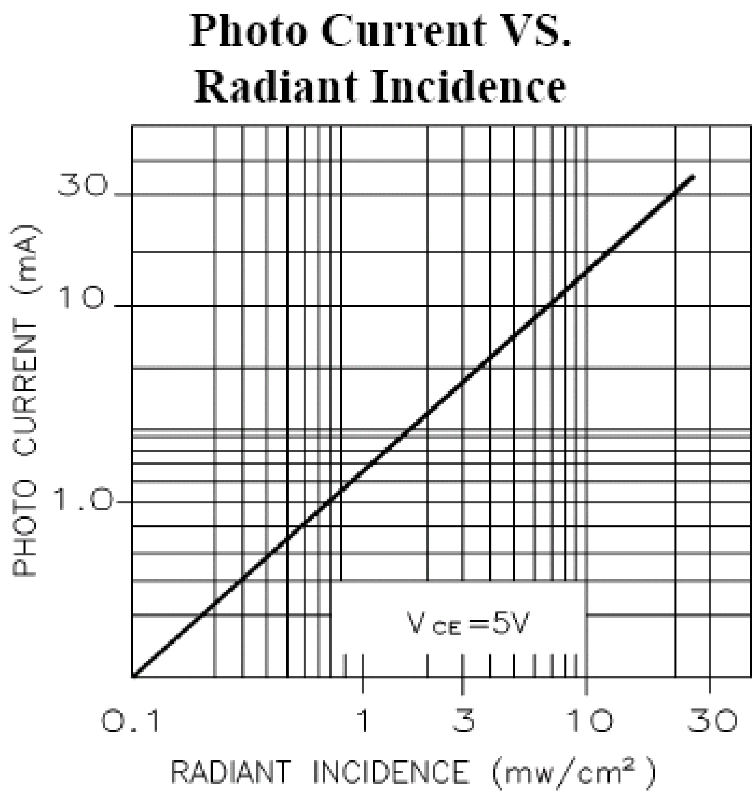
$$\boxed{I_p = e\eta P/(h\nu)}$$



where I is the total device current, I_p is the photocurrent, I_{dk} is the dark current (leakage current), V_0 is the voltage across the diode junction, q is the charge of an electron, k is Boltzmann's constant, and T is the temperature in degrees Kelvin. P= radiation energy, η= quantum coefficient

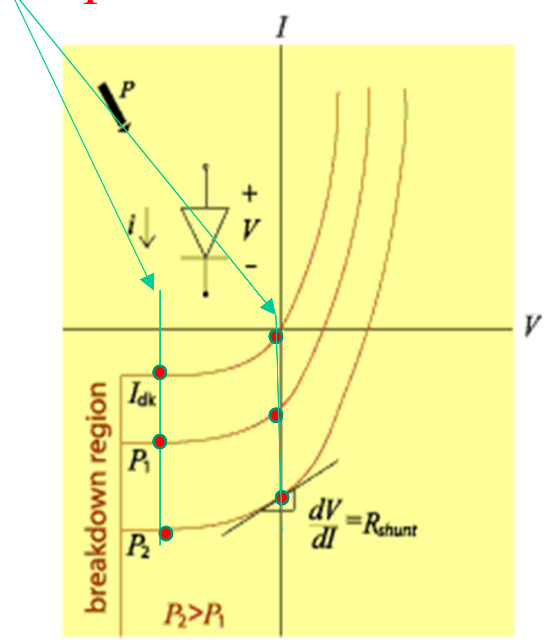
Two significant features to note from both the curve and the equation are that the photogenerated current (I_p) is additive to the diode current, and the dark current is merely the diode's reverse leakage current. Finally, the detector shunt resistance is the slope of the I-V curve (dV/dI) evaluated at V= 0.

Photodiode Light Sensitivity

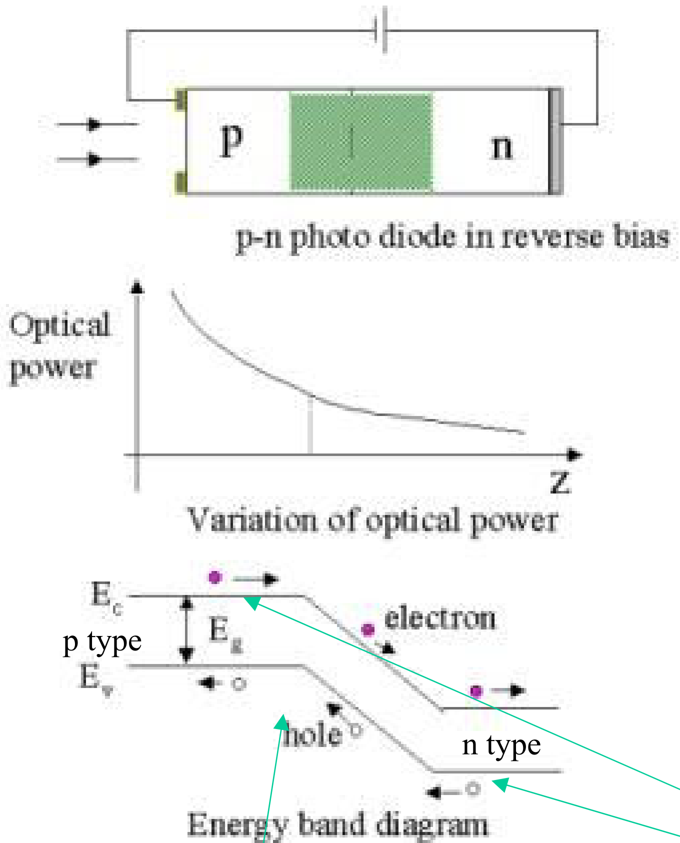


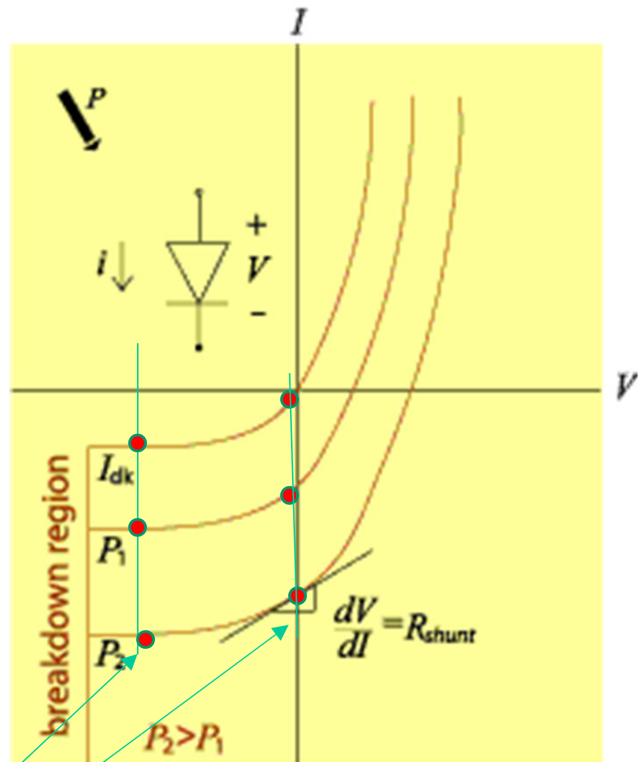
The current through a photodiode is directly proportional to the intensity of the incident light.

$I_d \sim I_p + I_{sat}$



Three key features happening in reverse bias



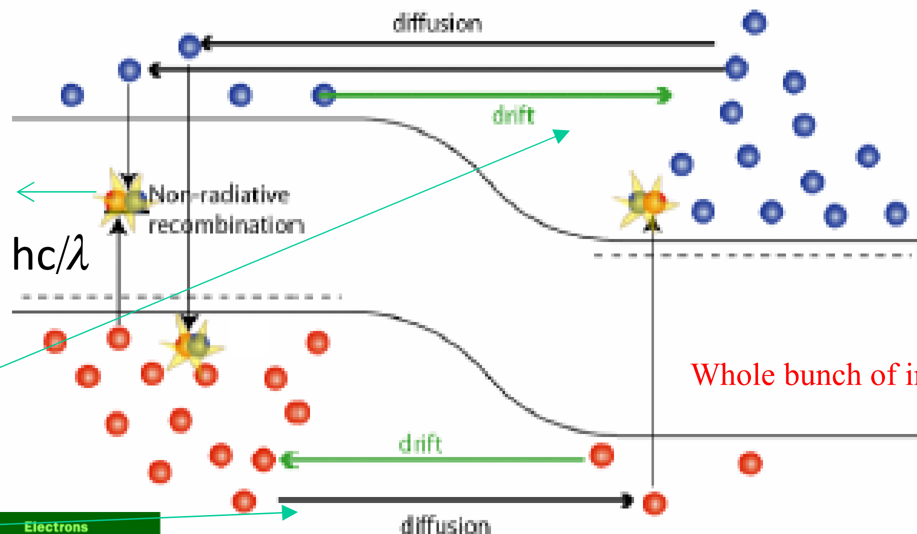


- Reverse bias current is mainly due to **minority carriers**
- **Photo current increases significantly in reverse bias**
- diffusion current outside the depletion region diffusion is slow process (**high potential barrier**)

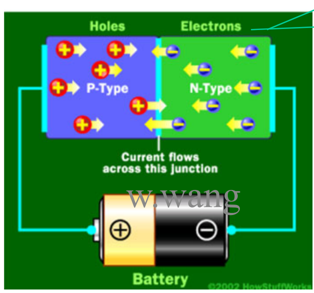
Forward and Reverse Bias

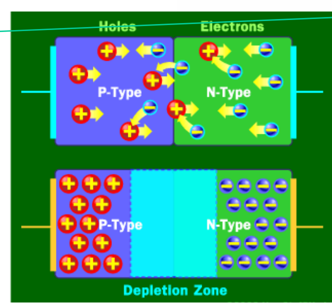
- Forward bias is a voltage applied to the pn junction that REDUCES the electric field at the barrier, Reverse bias INCREASES the electric field at the junction
- When bias is applied the balance between drift and diffusion current is destroyed – nett current flow
- In forward bias, drift current decreases very slightly (can assume it stays the same) but diffusion current increases – Nett current flow
- In reverse bias opposite occurs with diffusion current decreasing and drift remaining same – Nett current flow (this one isvery small)

$h\upsilon = hc/\lambda$

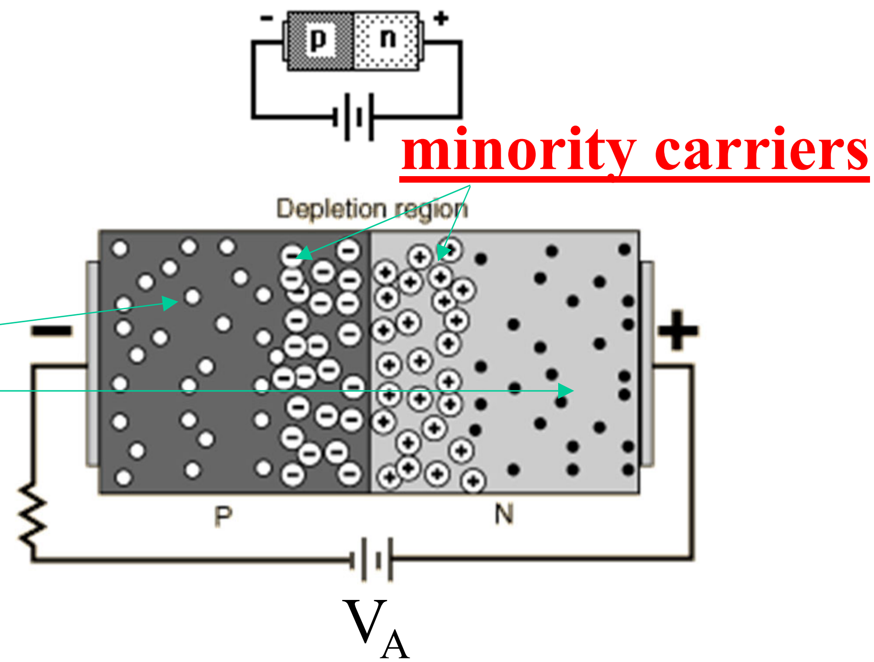


Whole bunch of interbands not shown





Depletion Widen with Increase Reverse Bias



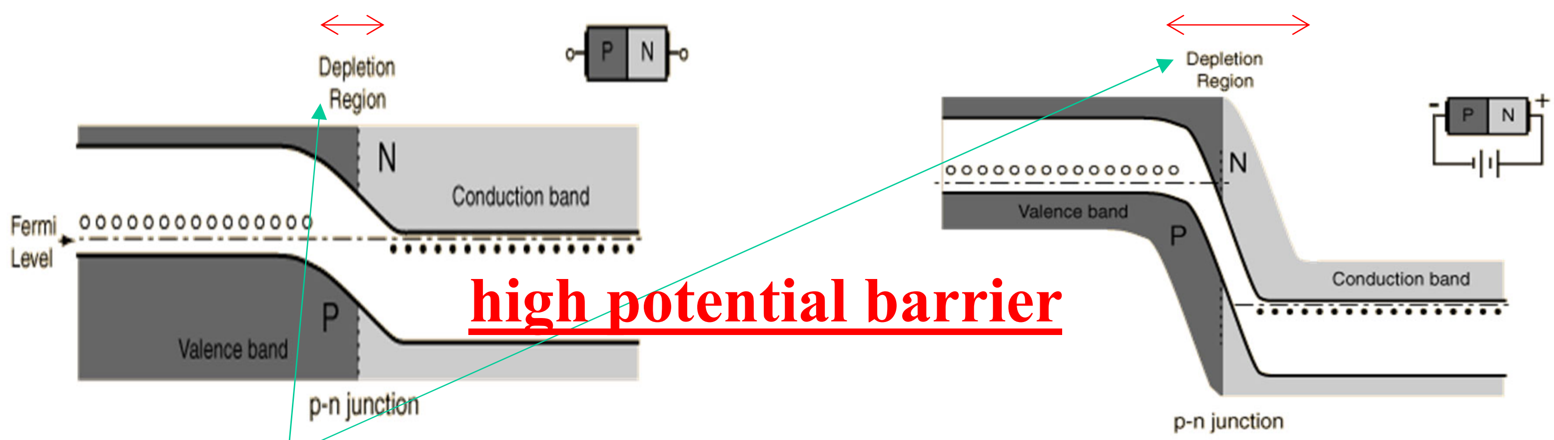
The application of a reverse voltage to the p-n junction will cause a transient current to flow as both electrons and holes are pulled away from the junction. When the potential formed by the widened depletion layer equals the applied voltage, the current will cease except for the small thermal current.

Depletion region width:

$$W = [2\varepsilon_r\varepsilon_o(V_{bi}-V_A)(N_A+N_D)/(q\,N_AN_D)]^{1/2}$$

$$i_D = I_S\left(e^{v_D/nV_T} - 1\right) \sim I_{sat} \text{ because } V_A \text{ is negative}$$

Potential Barrier Increase with Increase Reverse Bias

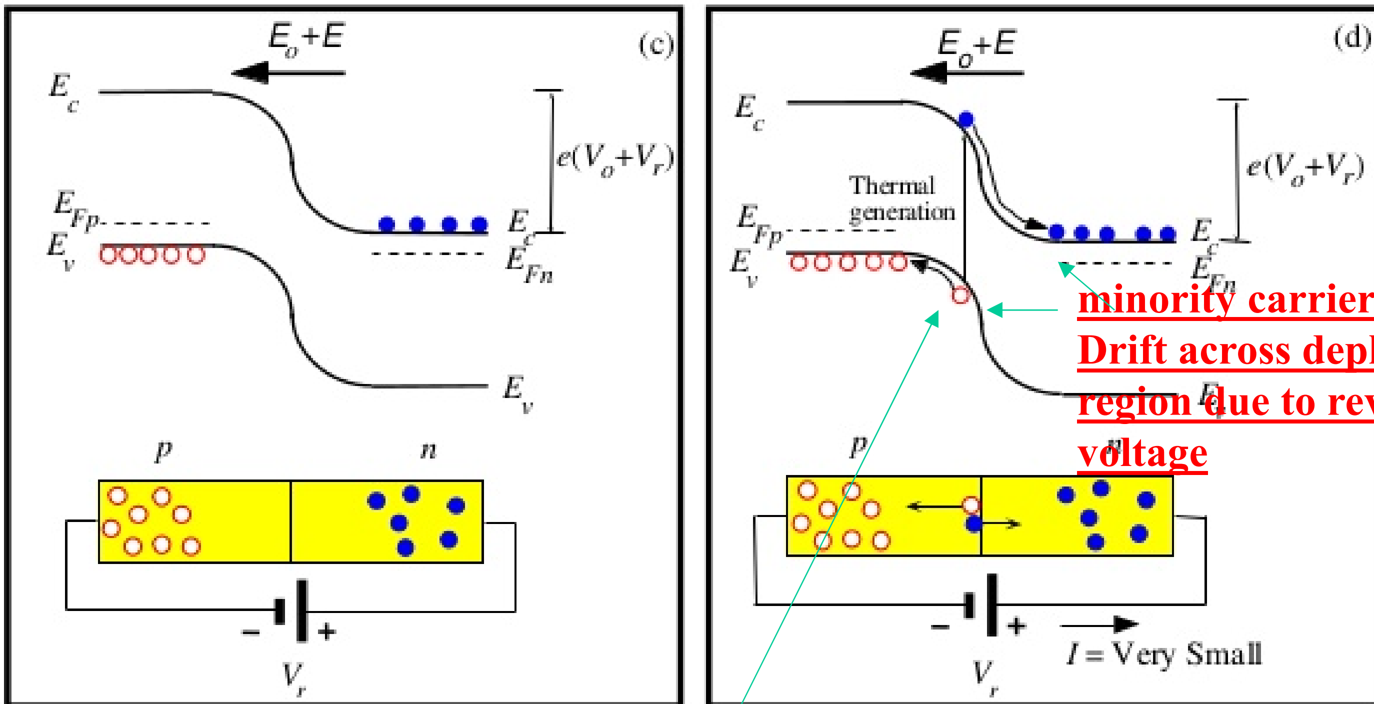


high potential barrier

$$W = [2\varepsilon_r\varepsilon_o(V_{bi}-V_A)(N_A+N_D)/(q\,N_AN_D)]^{1/2}$$

To reverse-bias the p-n junction, the p side is made more negative, making it "uphill" for electrons moving across the junction. The conduction direction for electrons in the diagram is right to left, and the upward direction represents increasing electron energy.

Thermal Current Due to minority carriers

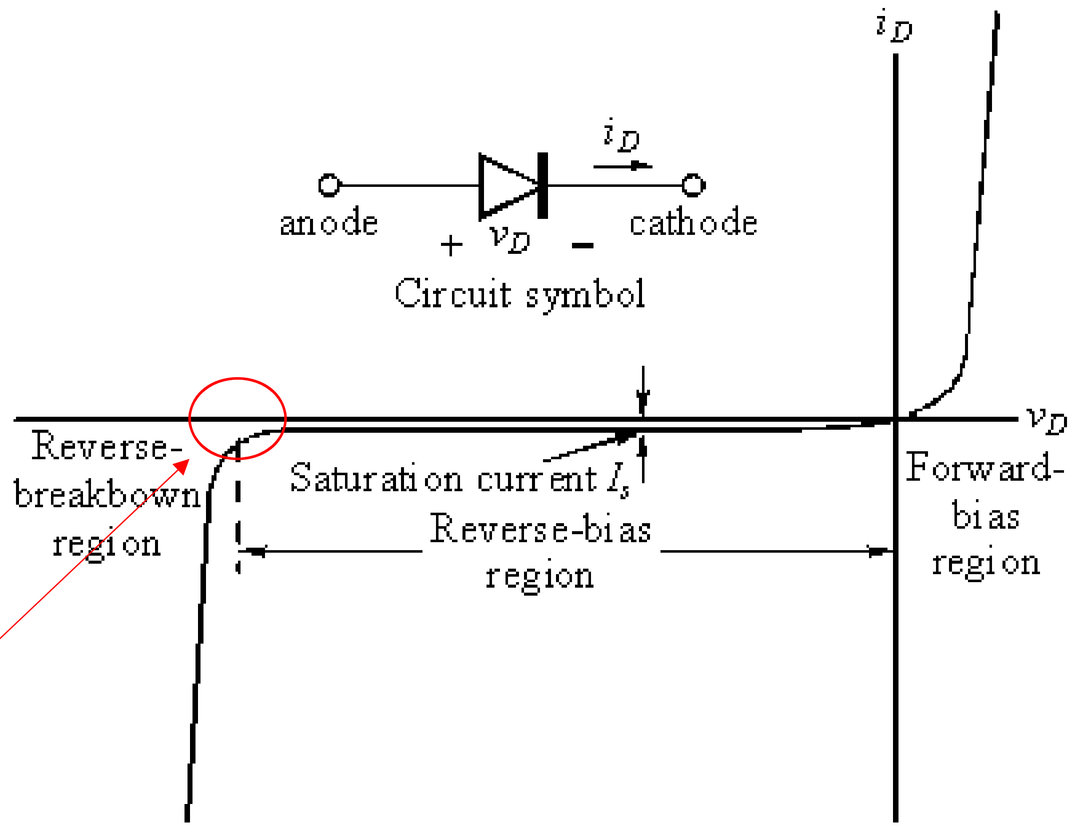


<u>**minority carriers Drift across depletion region due to reverse voltage**</u>

Energy band diagrams for a *pn* junction under (c) reverse bias conditions. (d) Thermal generation of electron hole pairs in the depletion region results in a small reverse current.

Maximum Reverse Voltage (Vr)

Applying excessive reverse voltage to photodiodes may cause breakdown and severe degradation of device performance. Any reverse voltage applied must be kept lower than the maximum rated vale, (Vr max).



Quantum efficiency

How well energy covert

A photodiode's capability to convert light energy to electrical energy, expressed as a percentage, is its Quantum Efficiency, (Q.E.).

$$\eta = r_e/r_p = \frac{\text{\# of electrons (holes) collected as } I_p\text{/sec}}{\text{\# of incident photons/sec}}$$

Depends on λ, through absorption coefficient, thickness of layers, Doping, geometry, etc. Operating under ideal conditions of reflectance, crystal structure and internal resistance, a high quality silicon photodiode of optimum design would be capable of approaching a Q.E. of 80%.

Photodiode Responsivity

How well power convert to current

Responsivity R_λ is defined as the ratio of radiant energy (in watts), P, incident on the photodiode to the photocurrent output in amperes I_p. It is expressed as the absolute responsivity in **amps per watt**. Please note that radiant energy is usually expressed as watts/cm^2 and that photodiode current as amps/cm^2. The cm^2 term cancels and we are left with amps/watt (A/W).

$$R_\lambda = \frac{I_p}{P} \qquad \text{(A/W)}$$

Since $h\upsilon$ = energy of photon, $P = r_p\, h\upsilon$

where r_p = photon flux = $P/h\upsilon$ = # photons/ sec

Recall QE is $\eta = r_e/r_p$

$P = r_p h\upsilon$

Electron rate then

$$r_e = \eta r_p = \eta P/(h\nu)$$

Therefore, the output photo current $I_p = e r_e$ is

$$I_p = e\eta P/(h\nu)$$

The responsivity $R_\lambda = \dfrac{I_p}{P}$ may then be written

$$R_\lambda = e\eta/(h\nu) = e\eta\lambda/(hc) = \eta\lambda/1.24 \text{ (A/W)}$$

Slope of the curve

h= plank constant = 6.63×10^{-34} joule-sec

Responsivity

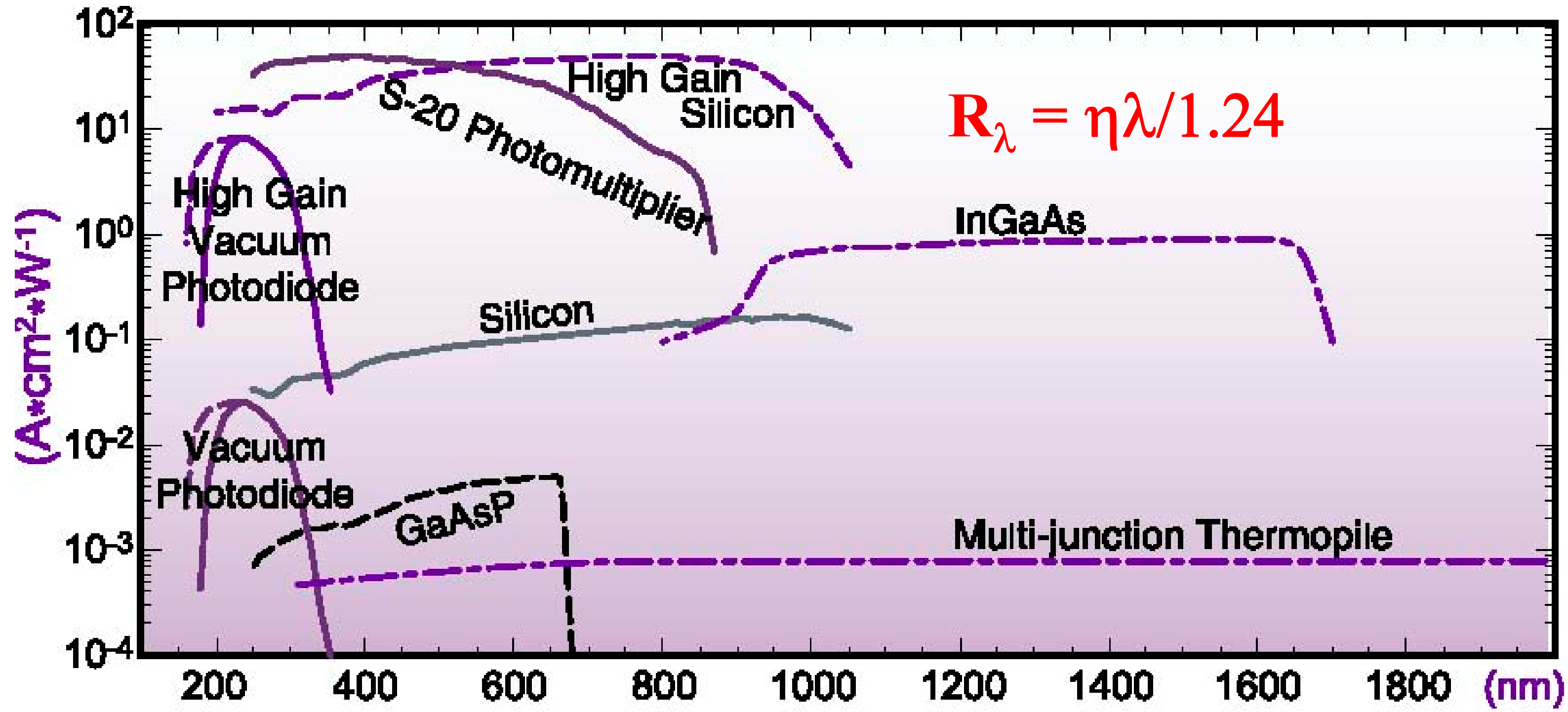
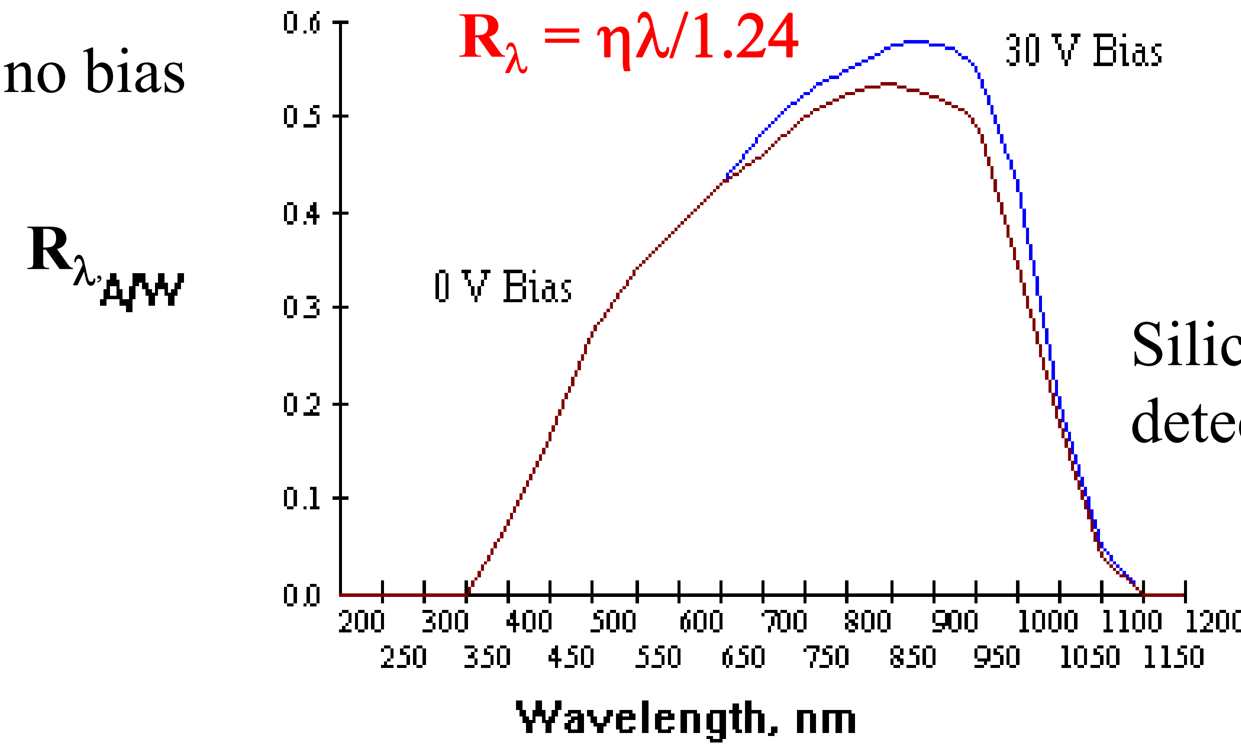


Fig. 10.1 Common detector types - absolute responsivity, unfiltered.

Responsivity

Bias or no bias



Silicone based detector

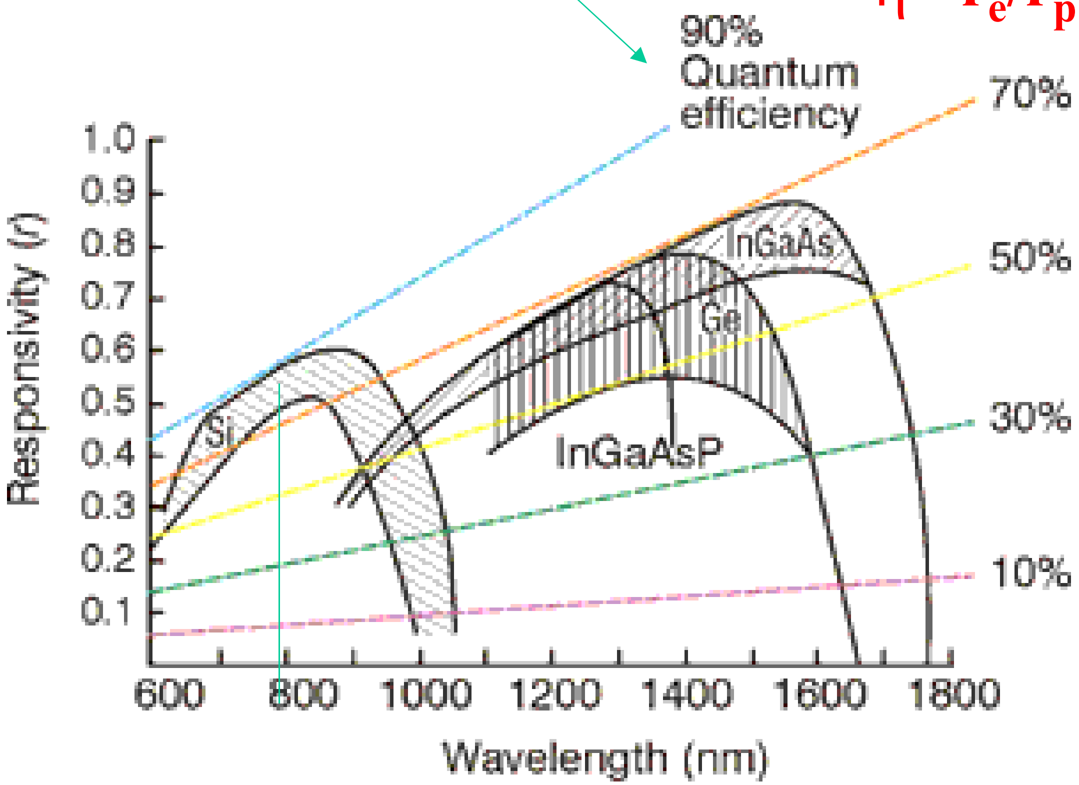
A typical responsivity curve that shows A/W as a function of wavelength

Responsivity and Quantum Efficiency

$R_\lambda = \eta\lambda/1.24$

$\eta = r_e/r_p$ Silicon ~ 90%

InGaAs ~ 70%



R_λ

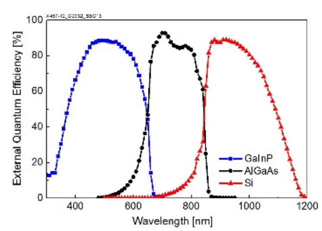
Silicon PN~ 0.41–0.7

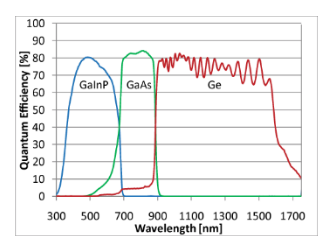
Silicon PIN ~ 0.6–0.8

InGaAs PIN ~0.85

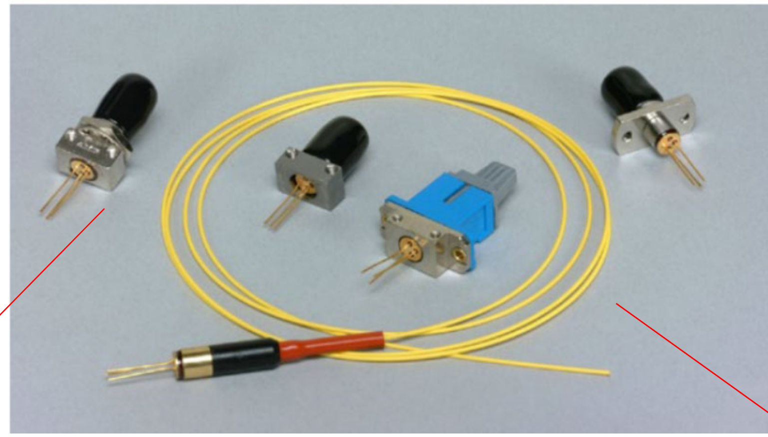
InGaAs APD ~0.8

Germanium ~0.7



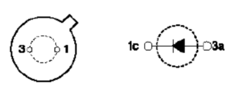


Si and InGaAs Detectors

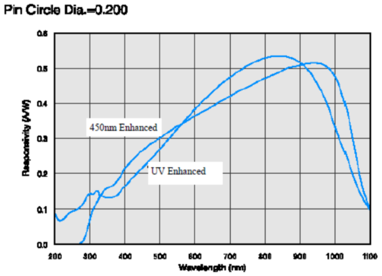


PD-LD Part Number	Active Area (mm)	Responsivity (A/W) Typical Values			Capacitance pF 0V Typ.	Shunt Resistance (G Ohm) -10mV		NEP (W/ root Hz) 0V 254nm 50 Ohm	Rise Time (u sec) 0V 254nm 50 Ohm
		254 nm	633nm	930nm		Min.	Typ		
170-10455-43	2.4 sq	0.10	0.33	0.50	100	0.30	4	2.0 e^{-14}	0.10

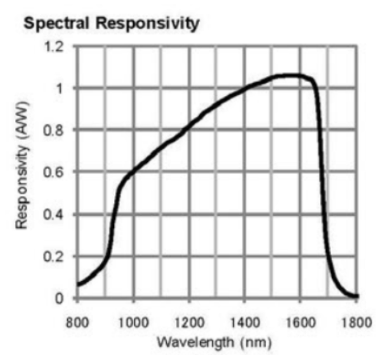
Absolute Maximums	
Operating Temperature	-20 to +85 °C
Storage Temperature	-55 to + 85 °C
Operating Current (0V)	0.1 mA
Reverse Voltage	5V



Pin Circle Dia.=0.200



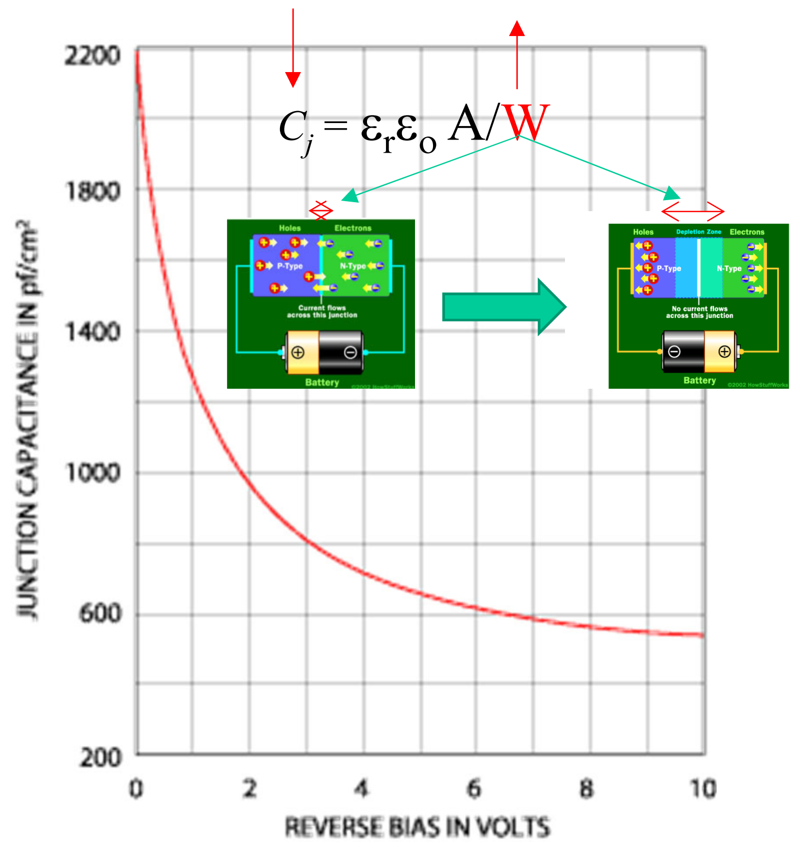
PD-LD Part Number	Active Area (µm)	Responsivity (A/W) Min.	Capacitance Typ.	Capacitance Max	Dark Current Typ.	Dark Current Max	Bandwidth -3dB (MHz)	Pin-Out
InGaAs (@ 5V bias, 1300nm Laser Source, 25°C								
PDINV300FC11-M-0	300	0.85	4.2	4.4	0.5	5.0	600	W
PDINV300FC21-M-0	300	0.85	4.2	4.4	0.5	5.0	600	W
PDINV300SC63-M-0	300	0.85	4.2	4.4	0.5	5.0	600	W



Junction Capacitance

When designing a sensing circuit to maximize the speed or linearity of response, one must know two important electrical characteristics of a photodiode: the junction capacitance and the shunt resistance. Without these, the *RC* time constant of the complete operating circuit cannot be calculated.

The parallel plate capacitance across the depletion region gives rise to a junction capacitance (C_j) which increases with the area A of the junction. Since increasing capacitance in a circuit slows its speed of response, photodiodes with smaller active areas are inherently capable of faster response than those with larger active areas. The junction capacitance is a function of the thickness of the depletion layer W, which varies with applied bias V_A, as shown in the graph. Therefore, it is common to specify the junction capacitance at zero external bias.



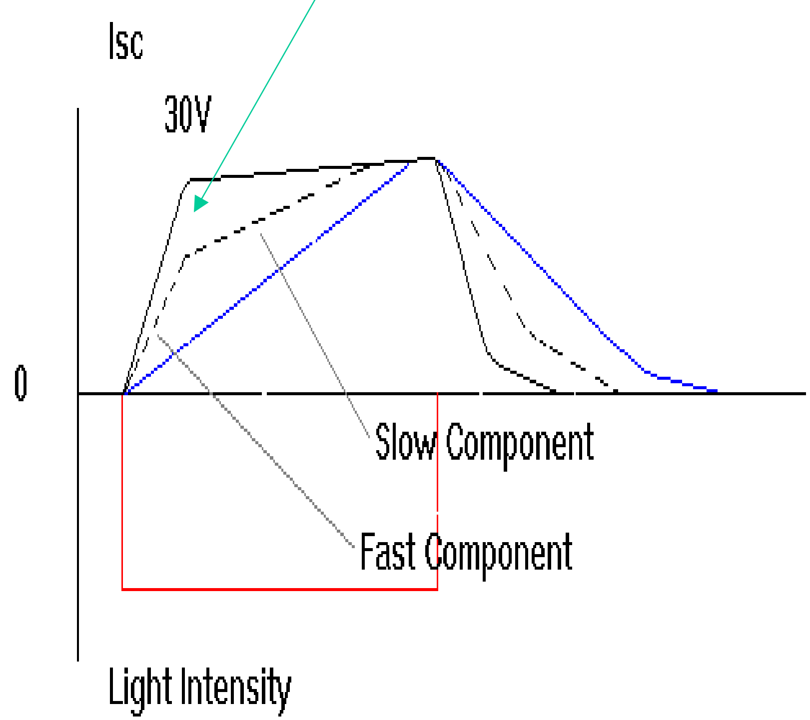
$$W = [2\varepsilon_r \varepsilon_o (V_{bi} - V_A)(N_A + N_D)/(q\, N_A N_D)]^{1/2}$$

Response Time

In many applications the most important parameter is dynamic performance. Photodiode response time is the root mean square sum of the charge collection time and the RC time constant arising from series plus load resistances and the junction and stray capacitances. **Charge collection time is voltage dependent** and is made up of a fast and a slow component. The fast component is the transit time of the charge carriers (electrons and holes) through the depletion region, producing carriers that are collected by diffusion. The transit time of these carriers will be relatively slow. The figure below illustrates the transient response of a photodiode to a square pulse of radiation.

Rise time (tr)

This is the measure of the photodiode response speed to a stepped light input signal. It is the time required for the photodiode to increase its output from 10% to 90% of final output level.

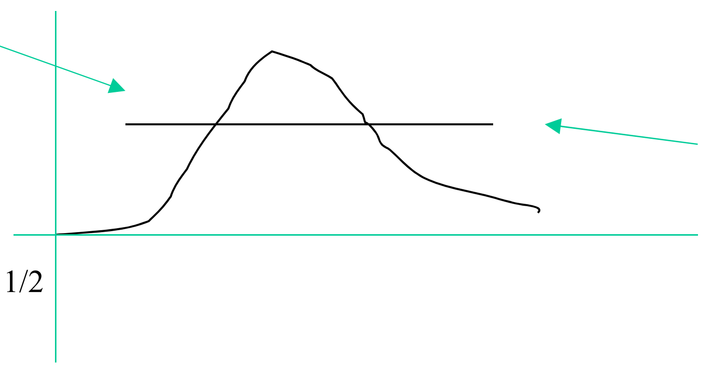


Response time

The time required for the detector to respond to an optical input. The response time is related to the bandwidth of the detector by

$$BW = 0.35/t_r \quad \propto \quad \text{Junction capcacitance}$$

where t_r is the rise time of the device. The rise time is the time it takes for the detector to rise to a value equal to 63.2% of its final steady-state reading.



1/RC

$$C_j = \varepsilon_r \varepsilon_o A/W$$

$$W = [2\varepsilon_r \varepsilon_o (V_{bi} - V_A)(N_A + N_D)/(q\, N_A N_D)]^{1/2}$$

Typical Photodetector Characteristics

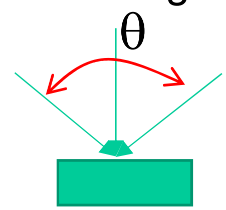
Photodetector	Wavelength (nm)	Responsivity (A/W)	Dark Current (nA)	Rise Time (ns)
Silicon PN	550–850	0.41–0.7	1–5	5–10
Silicon PIN	850–950	0.6–0.8	10	0.070
InGaAs PIN	1310–1550	0.85	0.5–1.0	0.005–5
InGaAs APD	1310–1550	0.80	30	0.100
Germanium	1000–1500	0.70	1000	1–2

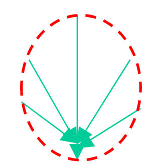
Detector Angular Response

The photocurrent generated from a photodiode is essentially independent of angle of incidence of the incoming radiation when the angle of incidence is **less than 30 degrees**. Typically, a variation in photocurrent of 1% to 2% can be expected, provided the detector's active area is underfilled, (i.e., the incoming radiation does not completely cover the device's entire active area). This condition assumes the photodiode's absorption layer thickness approximately equals the depletion layer thickness in the photodiode junction.

In circumstances where the photodiode is immersed in a collimated beam of incident light, the device's responsivity will fall off with the cosine of the angle of incidence as follows:

$$\mathcal{R}_{\theta} = \mathcal{R} \cos \theta$$




Detection pattern

where $\mathcal{R}$ is the photodiode responsivity at normal incidence.

Temperature Effects

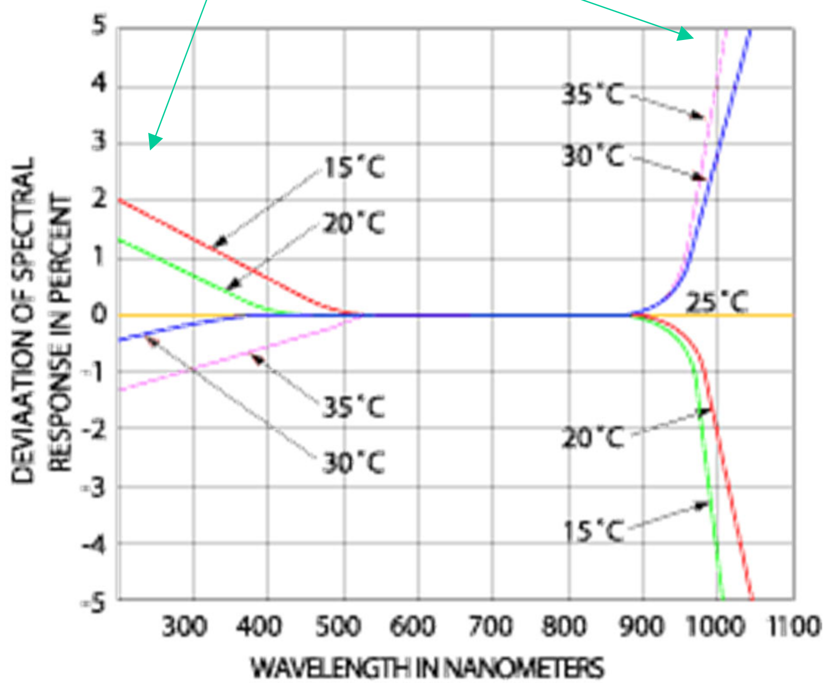
Typically, the dark current of a PNN+ silicon photodiode approximately doubles for each 10°C increase or decrease in the device temperature. The shunt resistance approximately doubles for each 6°C change:

$$I_{dk}(T_2) = I_{dk}(T_1) \cdot 2^{\frac{(T_2 - T_1)}{10}}$$

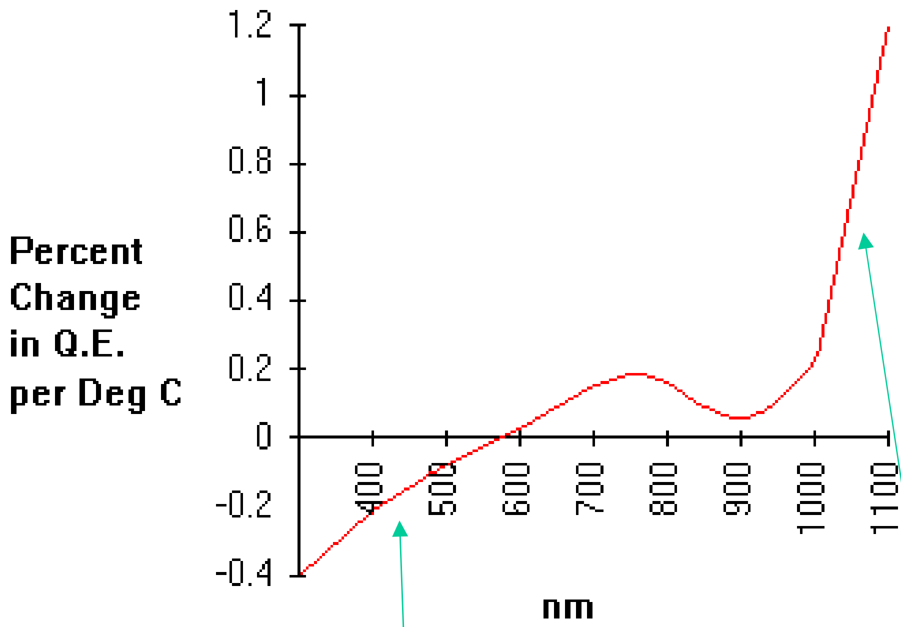
$$R_{shunt}(T_2) = R_{shunt}(T_1) \cdot 2^{\frac{(T_2 - T_1)}{6}}$$

These formulas can be used to calculate the shunt resistance and dark current for any temperature from the specified values, which are usually specified at 25°C.

Increasing the temperature of a semiconductor **shifts its absorption spectrum to longer wavelengths by reducing the effective band gap**. Fortunately, the absorption spectrum of silicon is quite broad. Consequently, the small temperature-induced shifts in the absorption spectrum only affect the responsivity significantly at the edges of the spectral responsivity curve, as shown in the figure below.



Temperature Effects

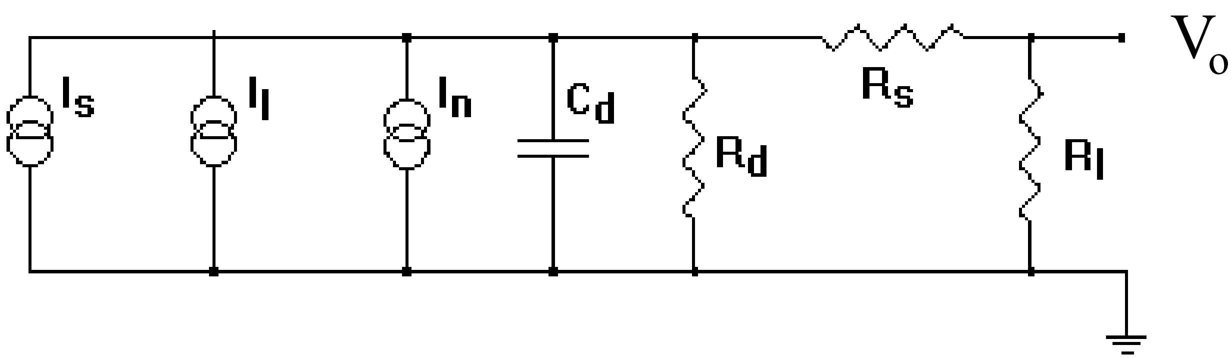


Temperature Dependence of Q.E.

Increasing the operating temperature of a photodiode device results in two distinct changes in operating characteristics. The first change is a shift in the Quantum Efficiency (Q.E.) due to changes in the radiation absorption of the device. Q.E. values shift lower in the UV region and higher in the IR region.

Equivalent Operating Circuits

A photodiode behaves as a photocontrolled current source in parallel with a semiconductor diode



I_s = signal current
I_l = leakage current
I_n = noise current
C_d = diode junction capacity

R_d = diode parallel shunt resistance
R_s = diode series resistance
R_l = load resistance

$$V_o = [I_s + I_l + I_n][R_l R_d] / [R_l + R_d + R_s]$$

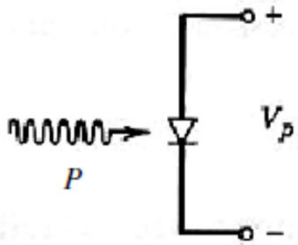
Bias of Photodiode

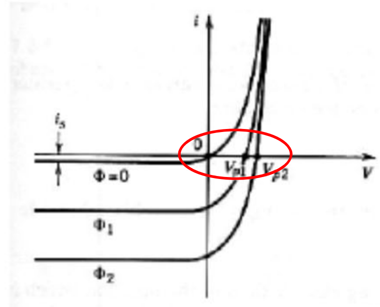
$$i = i_{rs}\left(e^{ev/K_BT} - 1\right) - i_p$$

$$i_p \equiv \eta e \frac{P}{h\nu}$$

Photovoltaic mode or Open circuit mode

Open circuit
- aka "Photovoltaic"
- Solar cells
- Low dark current
- Slow response



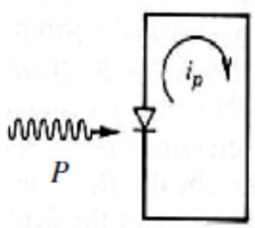


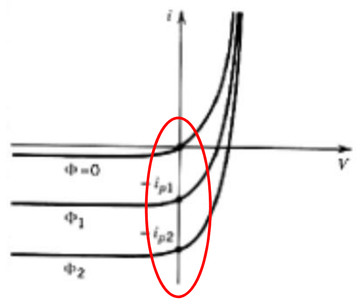
increase voltage like solar cell

i=0

Zero bias mode

Short circuit

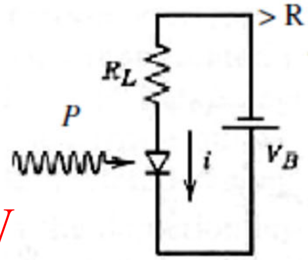




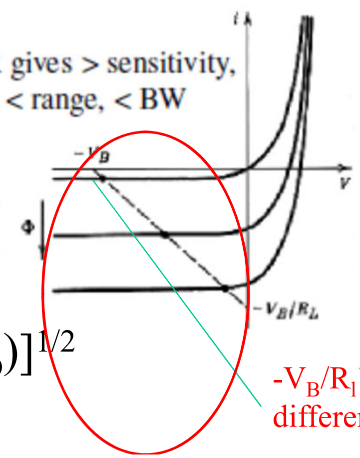
v=0

Reverse bias mode or Photoconductive mode

Reversed biased
- Drift field incr speed
- Lower capacitance " "
- Larger sensitive area



> R gives > sensitivity, < range, < BW



I_p varies with R_L

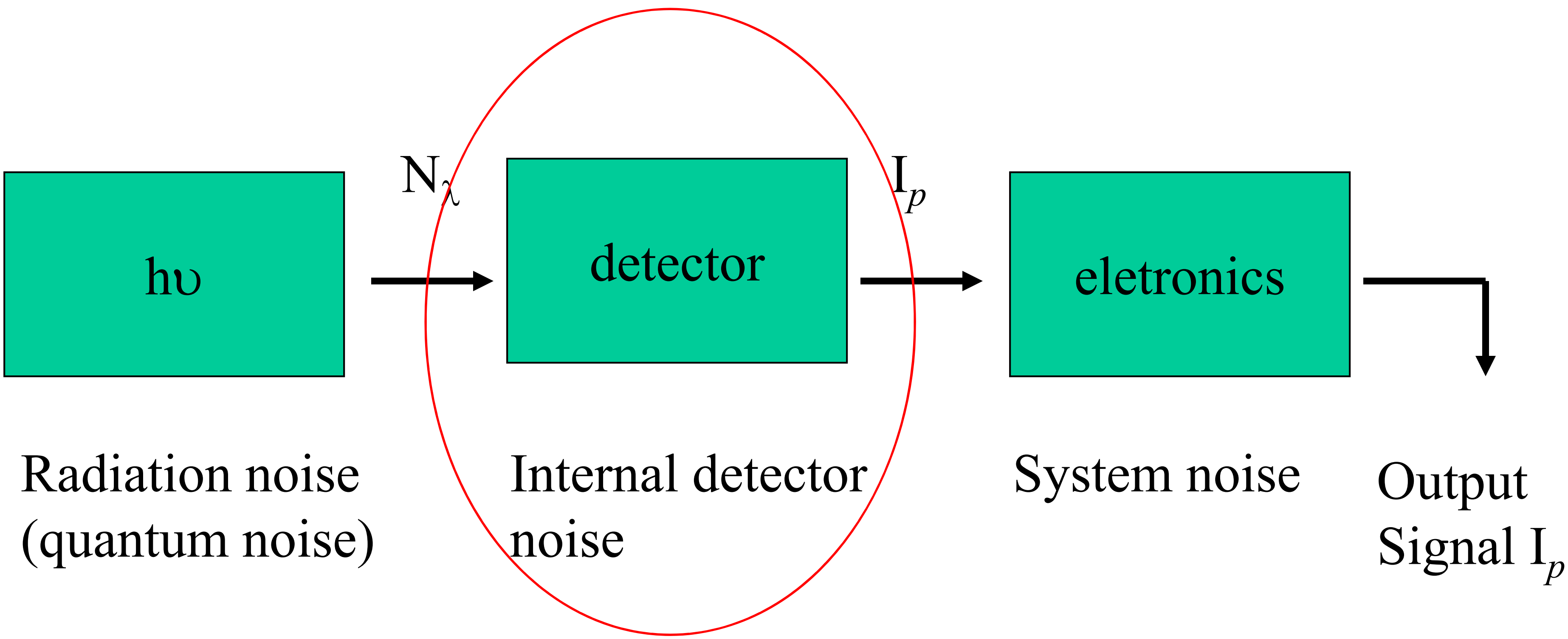
$$C_j = \varepsilon_r \varepsilon_o A/W$$

$$W = [2\varepsilon_r\varepsilon_o(V_{bi} - V_A)(N_A + N_D)/(q N_A N_D)]^{1/2}$$

$-V_B/R_l$' if load is different slope is different, different V will result for different I_p

w.wang

Noise in photodetectors



Four noise sources often encountered in connection with optical detectors.

- Johnson noise
- Shot noise
- $1/f$ noise
- Photon noise

Sources of internal detector noise

Johnson (thermal) noise

1. All resistive materials
2. Depends only on temp. and bandwidth of measuring system

The Johnson noise contribution is provided by <u>the shunt resistance of the device, series resistance and the load resistance</u>. The Johnson noise (<u>thermal noise</u>) is given by:

Johnson Noise Equation

$$I_j = \left(\frac{4KTB}{R} \right)^{1/2}$$

Where: I_j = Johnson noise current

K = Boltzmann constant (1.38 x 10   JK)

T = absolute temperature (K)

R = resistance giving rise to noise, Ohms

B = bandwidth of system, Hz

Johnson noise is generated by **thermal fluctuations** in conducting materials. It is sometimes called thermal noise. *It results from the random motion of electrons in a conductor*. The electrons are in constant motion, colliding with each other and with the atoms of the material. Each motion of an electron between collisions represents a tiny current. The sum of all these currents taken over a long period of time is zero, but their random fluctuations over short intervals constitute Johnson noise.

To reduce the magnitude of Johnson noise, one may **cool the system, especially the load resistor**. One should reduce the value of the load resistance, although this is done at the price of reducing the available signal. One should **keep the bandwidth of the amplification small**; one Hz is a commonly employed value.

Shot noise

- Seen in photodiodes under reverse bias (dark current noise) with no photon input,

$I = I_{sat} (e^{qV/kt} - 1) = -I_d$ (dark current)

$i_d^2 = 2eBI_d$ "white noise"

With light: $i_d^2 = 2eBI_p$ $I_p = e\eta P/(h\nu)$

where e = electronic charge and B=detection bandwidth.

The term *shot noise* is derived from ***fluctuations in the stream of electrons in a vacuum tube*****.** These variations create noise because of the random fluctuations in the arrival of electrons at the anode. The shot noise name arises from the similarity to the noise of a hail of shots striking a target.

In semiconductors, the major source of shot noise is **random variations in the rate at which charge carriers are generated and recombine**. **This noise, called generation-recombination or *gr noise*, is the semiconductor manifestation of shot noise.** Shot noise may be minimized by keeping any DC component to the current small, especially the dark current, and by keeping the **bandwidth of the amplification system small**.

1/f noise

Larger noise powers at lower frequencies.

No theory: not well understood.

Seems to be related to contacts, surfaces, other potential barrieres

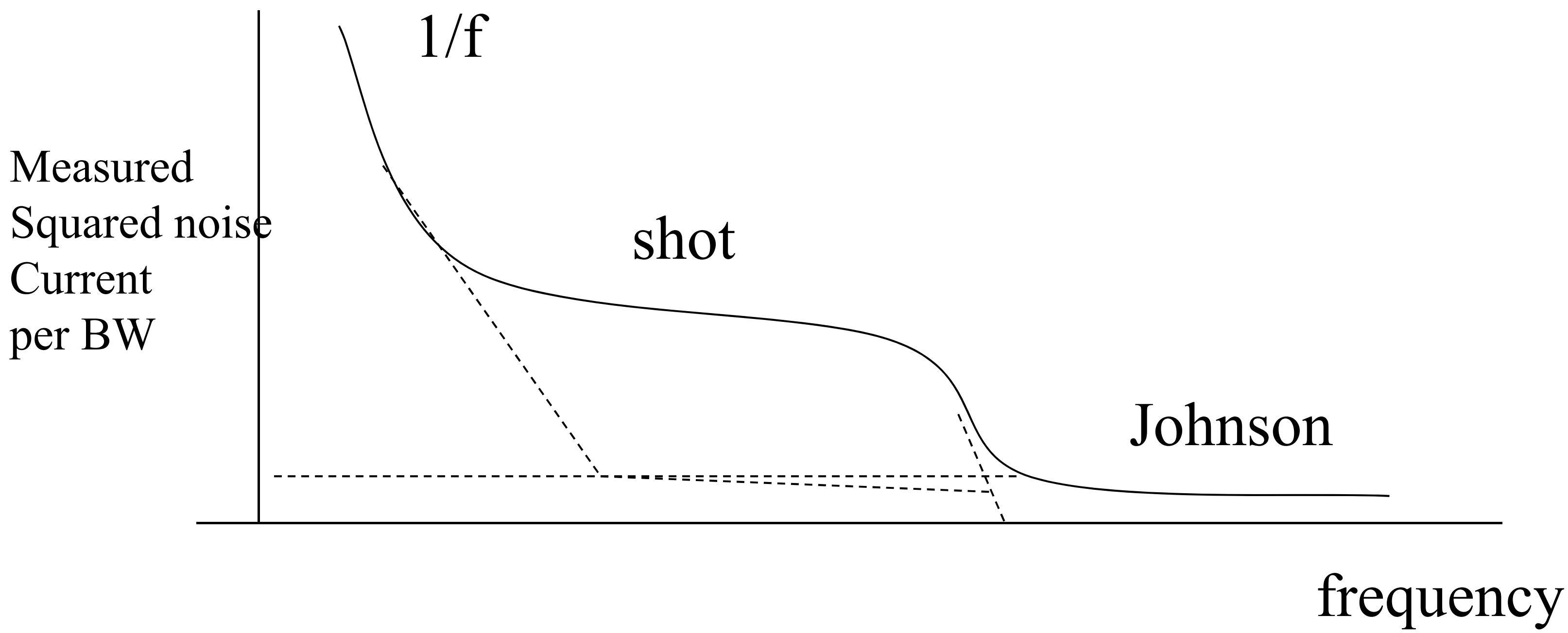
$$I_f^2 \sim I^2 B/f$$

B = bandwidth f = frequency

Usually much smaller than shot noise except at very low frequency

The term *1/*f *noise* (pronounced *one over f*) is used to describe a number of types of noise that are present when the modulation frequency *f* is low. This type of noise is also called excess noise because it exceeds shot noise at frequencies below a few hundred Hertz. The mechanisms that produce 1/*f* noise are poorly understood. The noise power is inversely proportional to *f*, the modulation frequency. This dependence of the noise power on modulation frequency leads to the name for this type of noise.
To reduce 1/*f* noise, an optical detector should be operated at a reasonably high frequency, often as high as 1000 Hz. This is a high enough value to reduce the contribution of 1/*f* noise to a small amount.

Noise spectrum



As an example: If a photodiode has a dark leakage current of 2 nA and a shunt resistance of 5x10^8 Ohms, and a responsivity of 0.5 A/W, and letting the bandwidth of the system be 1 Hz,

Shot Noise $I_s = 2.5 \times 10^{-14}$ A

Johnson Noise $I_j = 5.6 \times 10^{-15}$ A

Total Noise $= 2.6 \times 10^{-14}$ A

and NEP $= 5.1 \times 10^{-14}$ W

Noise-equivalent power (**NEP**) is a measure of the sensitivity of a photodetector or detector system. It is defined as the **signal power that gives a signal-to-noise ratio of one in a one hertz output bandwidth.**

As an example: If a photodiode has a dark leakage current of 2 nA and a shunt resistance of 5E8 Ohms, and a responsivity of 0.5 A/W, and letting the bandwidth of the system be 1 Hz,

Shot noise is the dominant component of the noise current of a reverse-biased photodiode. This is particularly true at higher voltages**. If devices are operated in a photovoltaic mode with zero bias, the Johnson noise dominates, as dark current approaches zero.** When operating in the zero bias mode the noise current is reduced such that the NEP, and hence the minimum detectable signal, is reduced in spite of some loss of absolute sensitivity.

Noise-equivalent power

Noise-equivalent power (NEP) is a measure of the sensitivity of a photodetector or detector system. It is defined as the signal power that gives a signal-to-noise ratio of one in a one hertz output bandwidth. An output bandwidth of one hertz is equivalent to half a second of integration time. The units of NEP are watts per square root hertz. The NEP is equal to the noise spectral density (expressed in units of $A/\sqrt{Hz}$ or $V/\sqrt{Hz}$ divided by the responsivity (expressed in units of A /W or V/W, respectively).

A smaller NEP corresponds to a more sensitive detector. For example, a detector with an NEP of 10^{-12} W/H z can detect a signal power of one picowatt with a signal-to-noise ratio (SNR) of **one after one half second of averaging**. The **SNR improves as the square root of the averaging time**, and hence the SNR in this example can be improved by a factor of 10 by averaging 100-times longer, i.e. for 50 seconds.

If the NEP refers to the signal power absorbed in the detector, it is known as the electrical NEP. If instead it refers to the signal power incident on the detector system, it is called the optical NEP. The optical NEP is equal to the electrical NEP divided by the optical coupling efficiency of the detector system.

Noise-equivalent power

Essentially, the NEP expresses the minimum detectable power per square root bandwidth of a given detector; in other words, it's a **measure of the weakest optical signal that can be detected.** Therefore, it is desirable to have an NEP as low as possible, since a low NEP value corresponds to a lower noise floor and therefore a more sensitive detector. Even at higher input intensities, a low NEP is beneficial since it will lead to lower noise characteristics in the output signal.

Even when blocking the optical input to a photodetector, there will be some amount of generated output noise (such as thermal or shot noise) that results in a certain average output noise power into the connected load. This noise power and thus the resulting noise-equivalent power, both depend on the related measurement bandwidth. This bandwidth is typically **normalized to 1 Hz**, which is usually **far below the detection bandwidth,** to **allow detectors with different bandwidth specifications to be directly compared.**

Minimum Detectable Optical Power

The Noise Equivalent Power depends on the optical wavelength as well, since the **responsivity of the detector is wavelength dependent**. For a given detector, the lowest NEP is achieved at the wavelength with maximum detector responsivity. To calculate the NEP at a different wavelength λ, the following formula can be used:

$$NEP(\lambda) = NEP_{min} \times \frac{R_{max}}{R(\lambda)}.$$

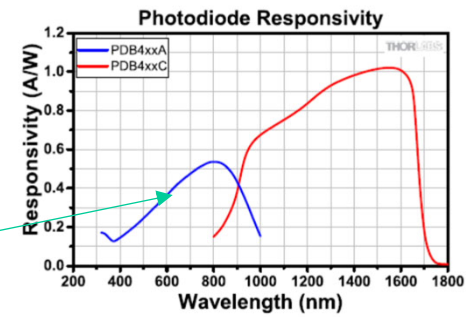


Figure 1: PDB4xxA and PDB4xxC detector responsivity

Here, *NEPmin* is the NEP as given in the specifications, *Rmax* is the maximum responsivity of the detector, and *R(λ)* is the responsivity of the detector at wavelength λ. Rmax and R(λ) can be read from the detector responsivity curves.

The NEP of a detector is the optical power incident to the detector that needs to be applied to equal the noise power from all sources in the detector; in other words, NEP is the optical power that results in an SNR of 1. Basically, **this represents the threshold above which a signal can be detected**. The **minimum detectable power Pmin** can be easily calculated using the following formula:

$$P_{min} = NEP(\lambda) \times \sqrt{BW}.$$

Here NEP(λ) is the wavelength-dependent NEP and BW is the measurement bandwidth **(how fast your device is operating at).**

Minimum detectable power (Noise floor)

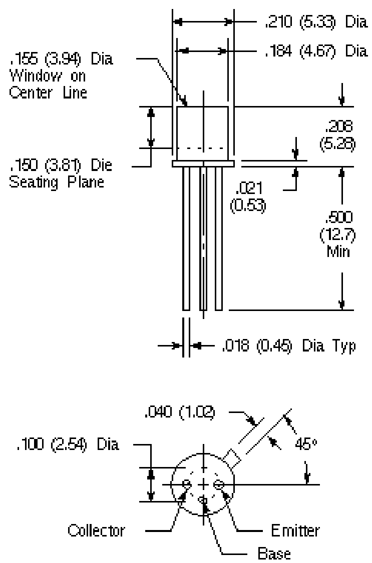
The noise floor is related to the dark current since the dark current will set the lower limit.

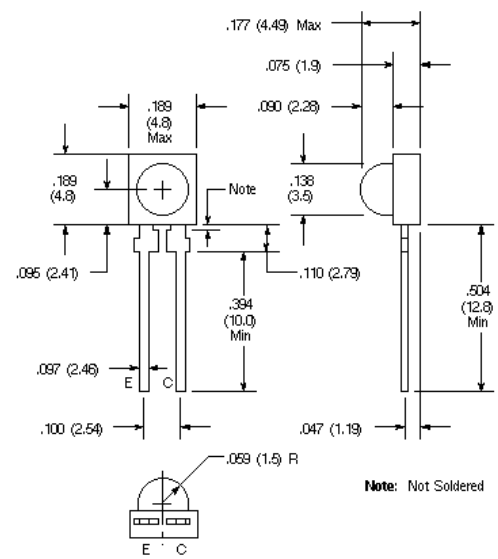
Noise floor = Noise (A)/Responsivity (A/W)

$$R_{\lambda} = \frac{I_p}{P}$$

Phototransistors

- Built in transistor amplifier
- Operate at zero bias mode

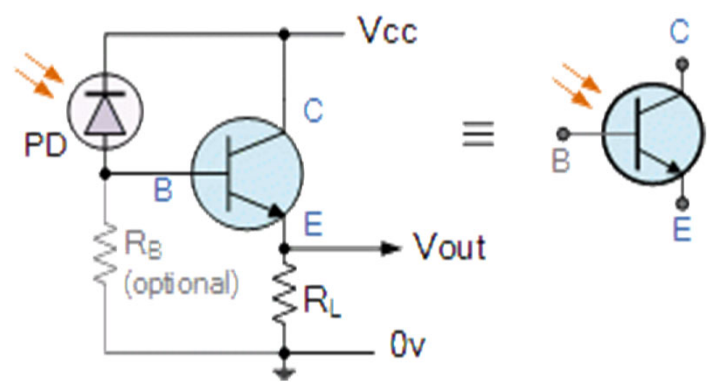




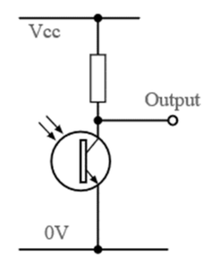
visay

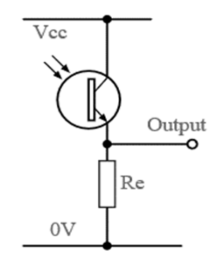
Phototransistors

Photo transistor basically is a LED operates in reverse mode connecting to a transistor. The light falling on a phototransistor creates charge carriers in the base region of a transistor, effectively providing base current. The intensity of the light determines the effective base drive and thus the conductivity of the transistor. Greater amounts of light cause greater currents to flow through the collector-emitter leads. Because a transistor is an active element having **current gain**, the phototransistor is more sensitive than a simple photoresistor or photodiode. However, the increased sensitivity comes at the price of reduced dynamic range. Dynamic range is the difference between the lowest and highest levels that can be measured. I think it depends on how you pick the resistor value. Normally photodiode is about 100ohm when it's on and 10Mohm when it's off. So that give you some idea what output voltage is going to be when you hook up to a resistor in series with the phototransistor.



How a phototransistor works is it has 2 terminals, an emitter and collector. It does not have a terminal connection to its base. The base is simply made up of infrared light-sensitive material. In a regular transistor, current or voltage needs to be applied to the base in order for the transistor to turn on and conduct.





Semiconductor

Variable conductivity

A pure semiconductor is a poor electrical conductor as a consequence of having just the right number of electrons to completely fill its **valence bonds**. Through various techniques (e.g., **doping or gating**), the semiconductor can be modified to have excess of electrons (becoming an ***n*-type semiconductor**) or a deficiency of electrons (becoming a ***p*-type semiconductor**). In both cases, the semiconductor becomes much more conductive (the conductivity can be increased by a factor of one million, or even more). Semiconductor devices exploit this effect to shape electrical current.

Junctions

When doped semiconductors are joined to metals, to different semiconductors, and to the same semiconductor with different doping, the resulting junction often strips the electron excess or deficiency out from the semiconductor near the junction. This depletion region is rectifying (only allowing current to flow in one direction), and used to further shape electrical currents in semiconductor devices.

Energetic electrons travel far

Electrons can be excited across the energy band gap of a semiconductor by various means. These electrons can carry their excess energy over distance scales of microns before dissipating their energy into heat, significantly longer than is possible in metals. This effect is essential to the operation of bipolar junction transistors.

Light energy conversion

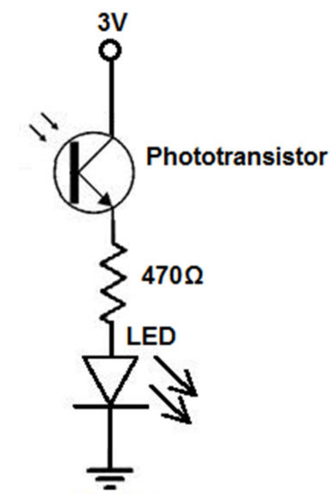
Electrons in a semiconductor can absorb light, and subsequently retain the energy from the light for a long enough time to be useful for producing electrical work instead of heat. This principle is used in the photovoltaic cell (e.g. solar cell). Conversely, in certain semiconductors, electrically excited electrons can relax by emitting light instead of producing heat. This is used in the light emitting diode.

Thermal energy conversion

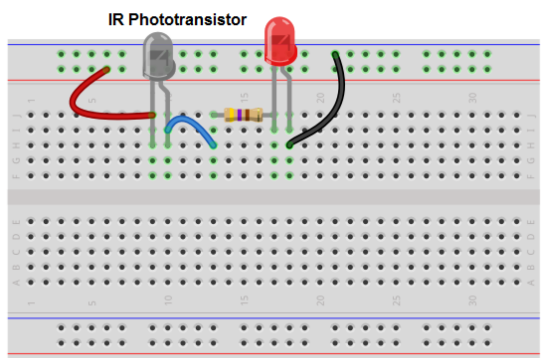
Semiconductors are good materials for thermoelectric coolers and thermoelectric generators, which convert temperature differences into electrical power and vice versa. Peltier coolers use semiconductors for this reason.

IR Phototransistor Receiver Circuit

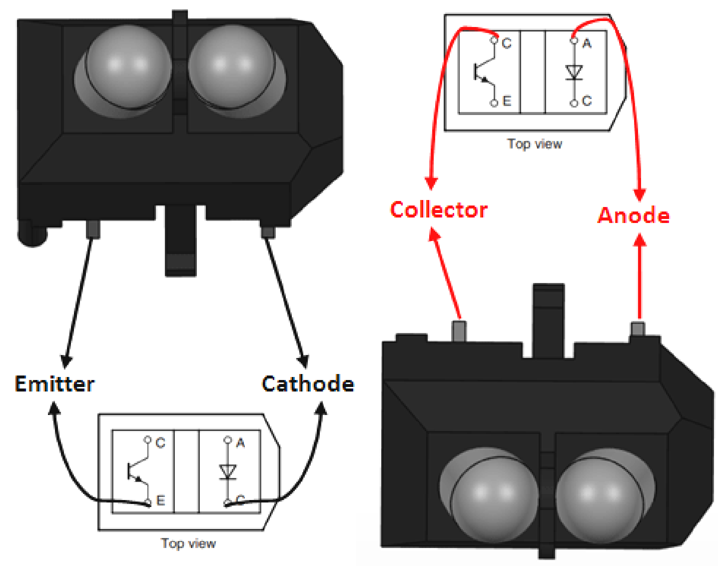
With an IR phototransistor, only infrared light will allow the transistor to turn on. Without infrared, the transistor will not turn on. When the IR phototransistor isn't exposed to any infrared light, there can be no current flow through the transistor, because infrared light is what produces base current in the transistor. The base current then allows and triggers a much larger current to flow from collector to emitter. Without infrared, there is no base current. Therefore, no amplified current can be produced from collector to emitter.



So if you expose the IR phototransistor to an infrared light source such as an infrared LED, a TV remote control, a flame, or sunlight, the LED will light up, assuming that the infrared light is of the wavelength that the IR phototransistor is designed to detect. This is because the infrared induces a base current in the transistor, which causes sufficient current amplification to drive and light the LED.



TCRT5000 IR Sensor



p-i-n Photodiodes

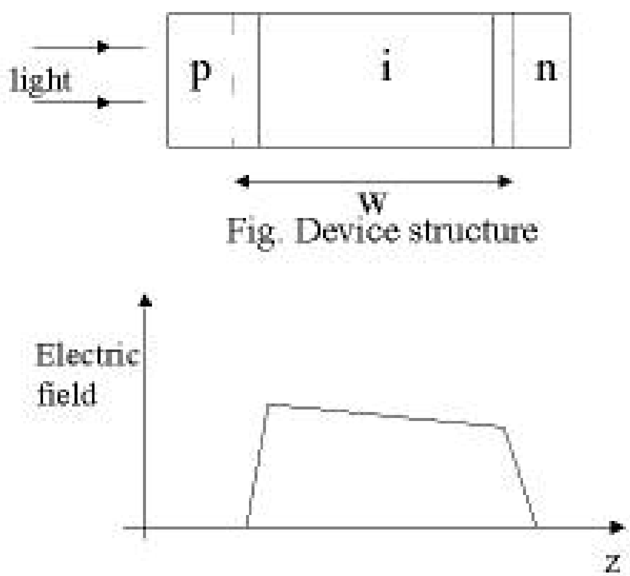


Fig. Device structure

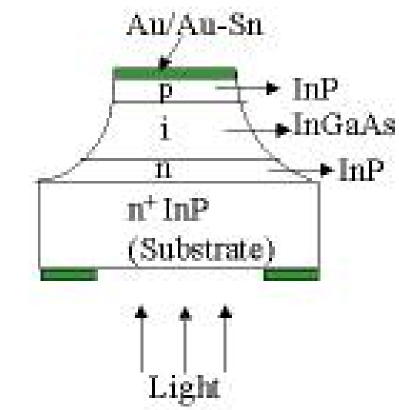


Fig. Fabrication structure

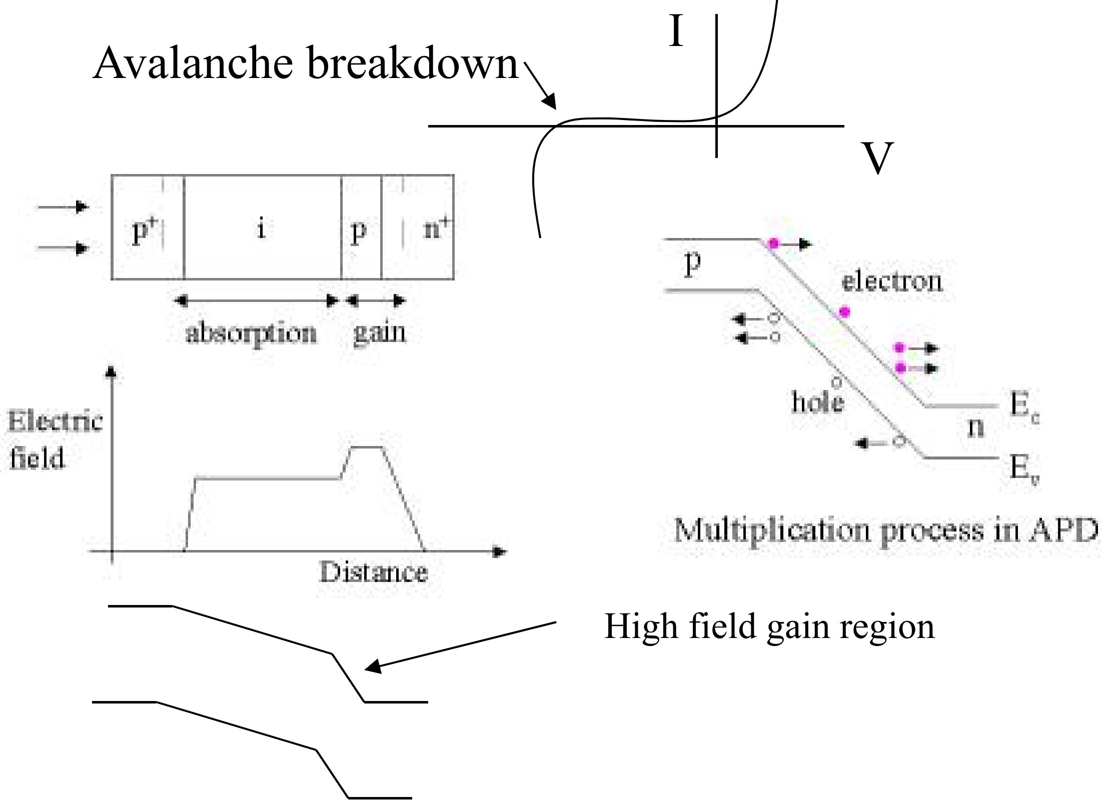
Mim Lal Nakarmi, KSU

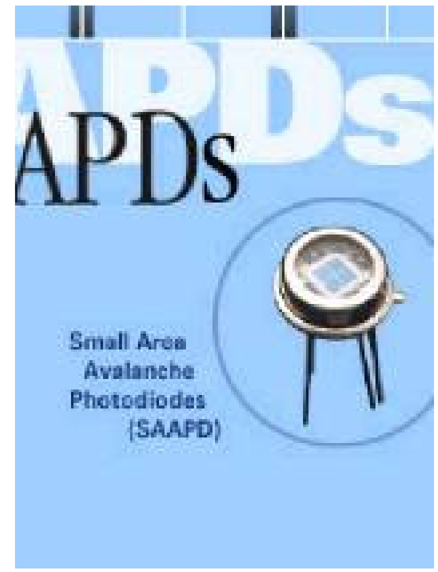
-As mentioned- **increasing deletion layer width improve quantum coefficient (more minority current flow due to larger barrier)**

=> **Lower doping increase deletion width (higher potential barrier)**

$$W = [2\varepsilon_r\varepsilon_o(V_{bi}-V_A)(N_A+N_D)/(q\, N_A N_D)]^{1/2}$$

Avalanche Photodiodes (APD)

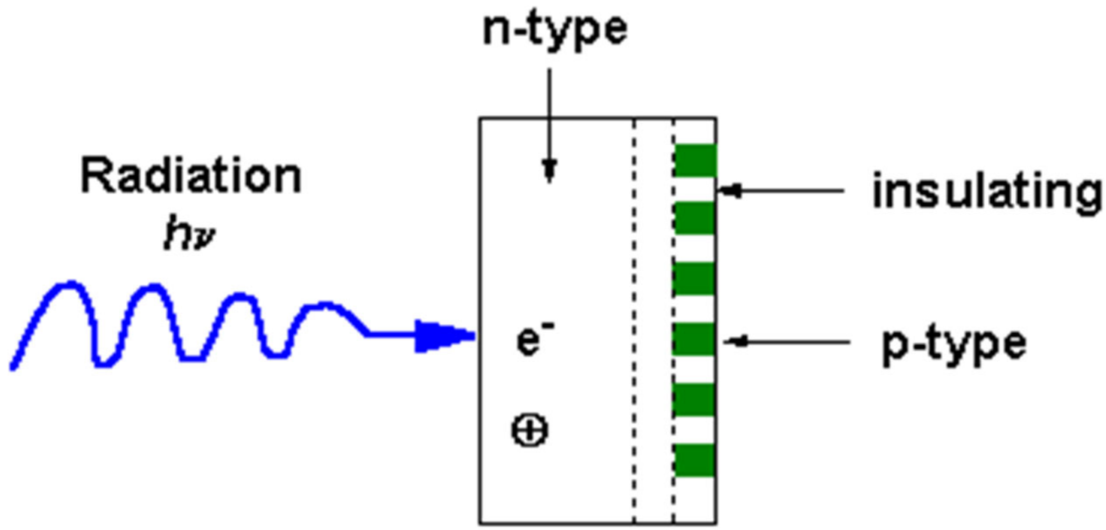




Mim Lal Nakarmi, KSU

- APD are designed to provide an internal current gain by impact ionization
- single primary electron/hole generated through absorption of a photon creates many secondary electrons and holes, all of which contribute to the photodiode current

Photodiode array (PDA)

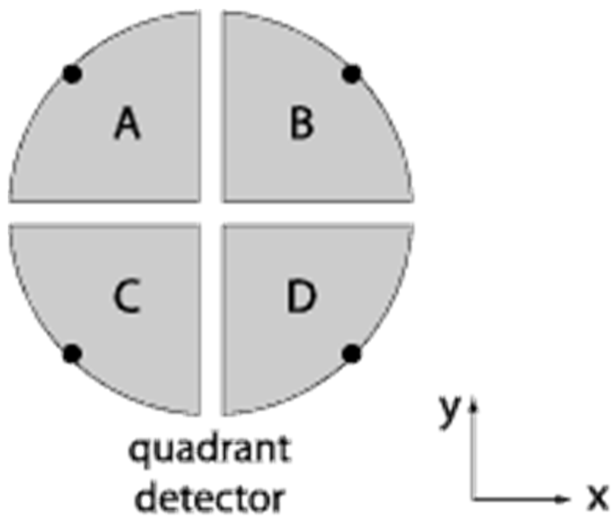


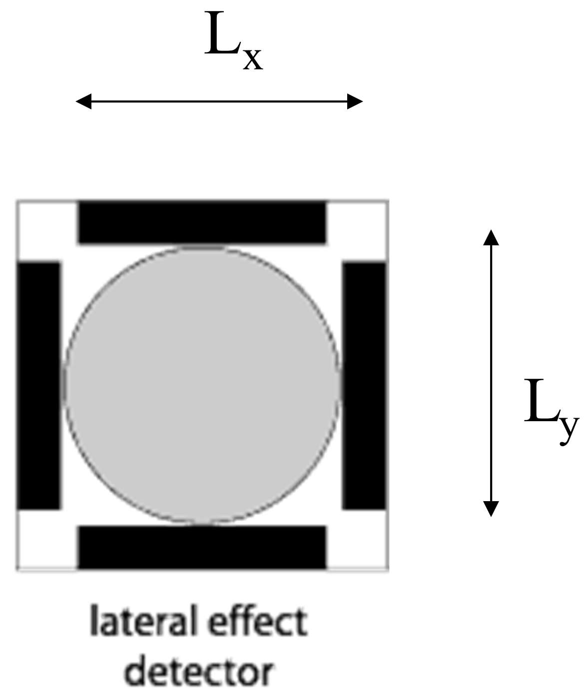
A photodiode array (PDA) is a linear array of discrete photodiodes on an integrated circuit (IC) chip. For spectroscopy it is placed at the image plane of a spectrometer to allow a range of wavelengths to be detected simultaneously. In this regard it can be thought of as an electronic version of photographic film. Array detectors are especially useful for recording the full uv-vis absorption spectra of samples that are rapidly passing through a sample flow cell, such as in an HPLC detector.

PDAs work on the same principle as simple photovoltaic detectors.

Position Sensing Detector

–Mm sensitivity
- limited by intensity and beam size





$$x = \frac{(b+d)-(a+c)}{a+b+c+d}$$

$$y = \frac{(a+b)-(a+d)}{a+b+c+d}$$

$$X = \frac{L_x}{2} \bullet \frac{X_1 - X_2}{X_1 + X_2}$$

$$Y = \frac{L_y}{2} \bullet \frac{Y_1 - Y_2}{Y_1 + Y_2}$$

Charge coupled detector array (CCD)

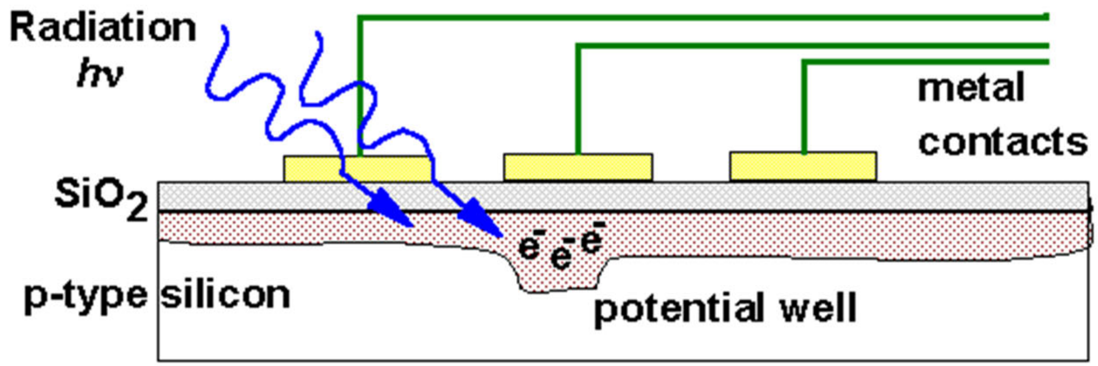
Charge Coupled Device was invented in the late 1960s by researchers at Bell Labs, The CCD's superb ability to detect light has turned it into the industry-standard image sensor technology.

CCD Basics

CCD imaging is performed in a three-step process:

1. Exposure, which converts light into an electronic charge at discrete sites called pixels
2. Charge transfer, which moves the packets of charge within the silicon substrate
3. Charge-to-voltage conversion and output amplification.

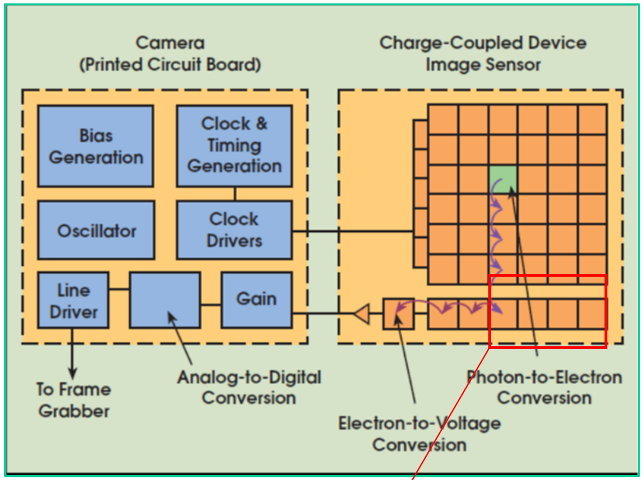
Charge coupled detector array (CCD)

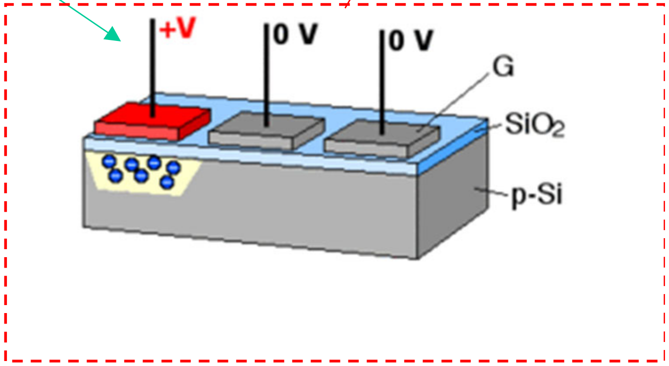


A CCD is an integrated-circuit chip that contains an array of capacitors (MOSFET) that store charge when light creates e-hole pairs. The charge accumulates and is read in a fixed time interval. CCDs are used in similar applications to other array detectors such as photodiode arrays, although the CCD is much more sensitive for measurement of low light levels.

Charge coupled detector array (CCD)

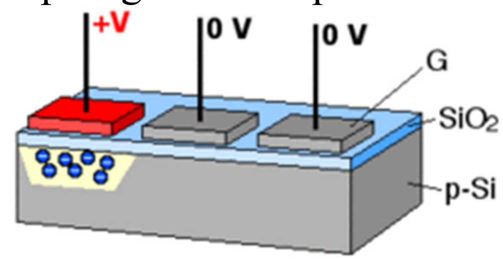
An image is projected through a lens onto the capacitor array (the photoactive region), causing each capacitor to accumulate an electric charge proportional to the light intensity at that location. A one-dimensional array, used in line-scan cameras, captures a single slice of the image, whereas a two-dimensional array, used in video and still cameras, captures a two-dimensional picture corresponding to the scene projected onto the focal plane of the sensor. Once the array has been exposed to the image, a control circuit causes each capacitor to transfer its contents to its neighbor (operating as a shift register). The last capacitor in the array dumps its charge into a charge amplifier, which converts the charge into a voltage. By repeating this process, the controlling circuit converts the entire contents of the array in the semiconductor to a sequence of voltages. In a digital device, these voltages are then sampled, digitized, and usually stored in memory; in an analog device (such as an analog video camera), they are processed into a continuous analog signal (e.g. by feeding the output of the charge amplifier into a low-pass filter), which is then processed and fed out to other circuits for transmission, recording, or other processing.





Charge coupled detector array (CCD)

Before the MOS capacitors are exposed to light, they are biased into the depletion region; in n-channel CCDs, the silicon under the bias gate is slightly *p*-doped or intrinsic. The gate is then biased at a positive potential, above the threshold for strong inversion, which will eventually result in the creation of a *n* channel below the gate as in a MOSFET. However, it takes time to reach this thermal equilibrium: up to hours in high-end scientific cameras cooled at low temperature. Initially after biasing, the holes are pushed far into the substrate, and no mobile electrons are at or near the surface; the CCD thus operates in a non-equilibrium state called deep depletion. Then, when electron–hole pairs are generated in the depletion region, they are separated by the electric field, the electrons move toward the surface, and the holes move toward the substrate. Four pair-generation processes can be identified:

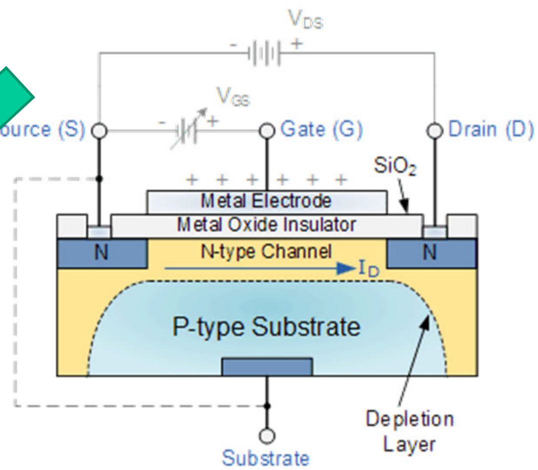


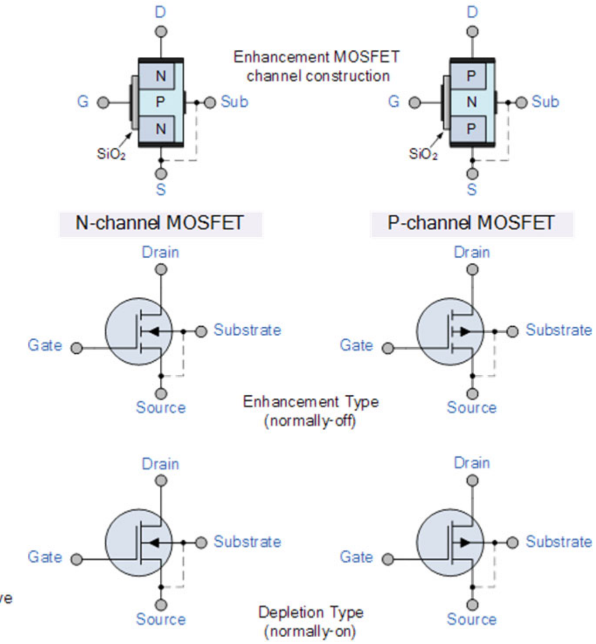
•photo-generation (up to 95% of quantum efficiency),
•generation in the depletion region,
•generation at the surface, and
•generation in the neutral bulk.

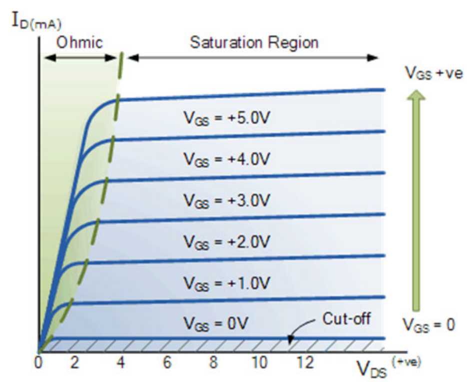
The last three processes are known as dark-current generation, and add noise to the image; they can limit the total usable integration time. The accumulation of electrons at or near the surface can proceed either until image integration is over and charge begins to be transferred, or thermal equilibrium is reached. In this case, the well is said to be full. The maximum capacity of each well is known as the **well depth,** typically about 10^5 electrons per pixel.

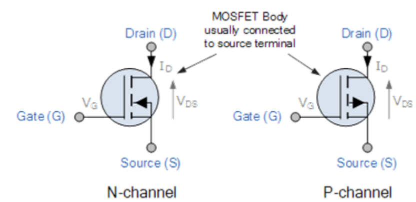
MOSFET

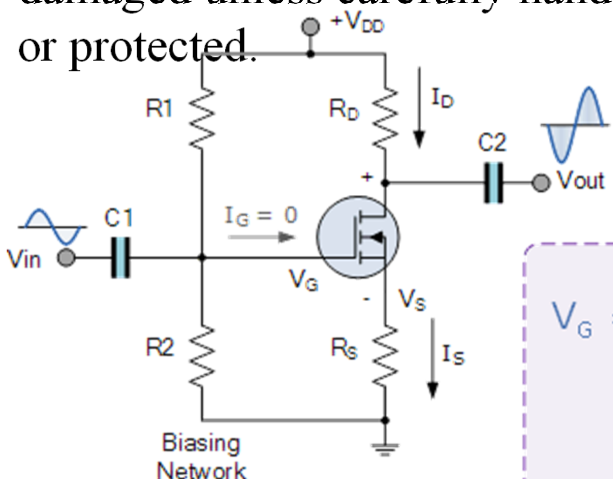
MOSFET also acts like <u>a voltage controlled resistor</u> where the **current flowing through the main channel between the Drain and Source is proportional to the input voltage.** Also like the JFET, the MOSFETs very high input resistance can easily accumulate large amounts of static charge resulting in the **MOSFET** becoming easily damaged unless carefully handled or protected.











$$V_G = \left(\frac{R2}{R1 + R2}\right) V_{DD}$$

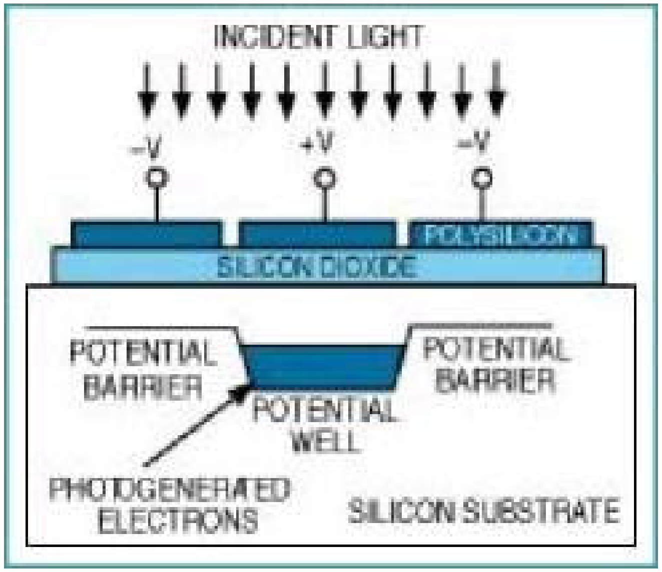
$$I_D = \frac{V_S}{R_S}$$

Enhancement-mode MOSFETs make excellent electronics switches due to their low "ON" resistance and extremely high "OFF" resistance as well as their infinitely high input resistance due to their isolated gate. Enhancement-mode MOSFETs are used in integrated circuits to produce CMOS type *Logic Gates* and power switching circuits in the form of as PMOS (P-channel) and NMOS (N-channel) gates. CMOS actually stands for *Complementary MOS* meaning that the logic device has both PMOS and NMOS within its design.

Electronics Tutorial

complementary metal oxide semiconductor (CMOS)

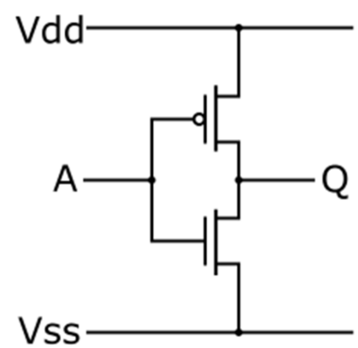
Charge is collected in potential well created by applying a voltage to the polysilicon, or gate electrode. The charge is confined in the well associated with each pixel by surrounding zones of higher potential barrier.



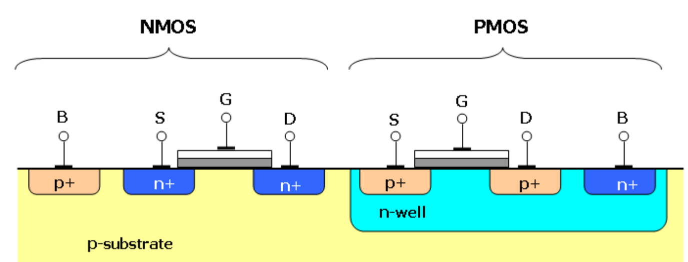
Mim Lal Nakarmi, KSU

CMOS

Complementary metal–oxide–semiconductor, abbreviated as CMOS**, is a technology for constructing integrated circuits**. CMOS technology is used in **microprocessors, microcontrollers, static RAM, and other digital logic circuits**. CMOS technology is also used for several analog circuits such as **image sensors (CMOS sensor), data converters**, and highly integrated transceivers for many types of communication. In 1963, while working for Fairchild Semiconductor, Frank Wanlass patented CMOS (US patent 3,356,858). CMOS is also sometimes referred to as complementary-symmetry metal–oxide–semiconductor (or COS-MOS).[1] The words "complementary-symmetry" refer to the fact that the typical design style with CMOS uses complementary and symmetrical pairs of p-type and n-type metal oxide semiconductor field effect transistors (MOSFETs) for logic functions



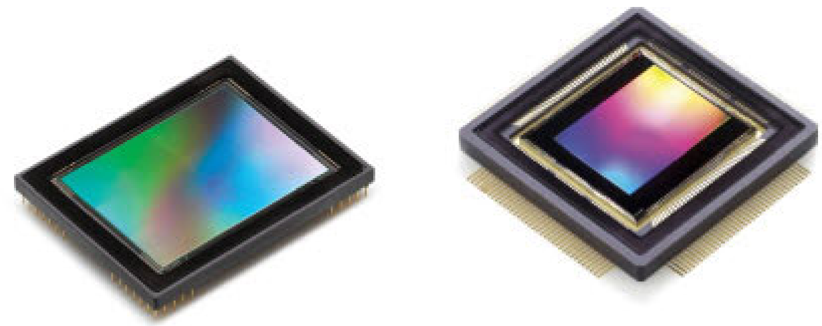
CMOS inverter



Cross section of two transistors in a CMOS gate, in an N-well CMOS process

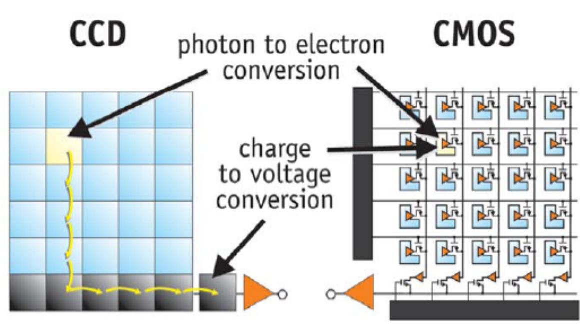
Difference between CCD and CMOS

- One difference between CCD and CMOS sensors is the way they capture each frame. A CCD uses what's called a **"Global Shutter"** while CMOS sensors use a **"Rolling Shutter".** Global Shutter means that the entire frame is captured at the exact same time.
- In a CCD sensor, every pixel's charge is transferred through a very limited number of output nodes (often just one) to be converted to voltage, buffered, and sent off-chip as an analog signal. All of the pixel can be devoted to light capture, and the output's uniformity (a key factor in image quality) is high.



Teledyne DALSA CCD (left) and CMOS (right) image sensors

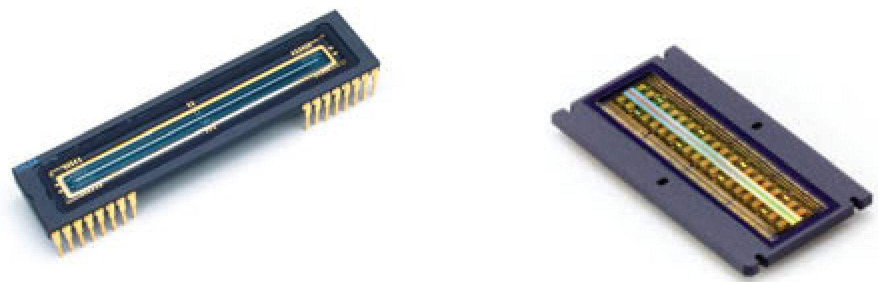
- CMOS sensor, each pixel has its own charge-to-voltage conversion, and the sensor often also includes amplifiers, noise-correction, and digitization circuits, so that the chip outputs digital bits. These other functions increase the **design complexity and reduce the area available for light capture**. With each pixel doing its own conversion, uniformity is lower, but it is also massively parallel, allowing high total bandwidth for high speed.



CCDs move photogenerated charge from pixel to pixel and convert it to voltage at an output node. CMOS imagers convert charge to voltage inside each pixel.

Difference between CCD and CMOS

- CCD became dominant, primarily because they gave far superior images with the fabrication technology available. CMOS image sensors required more uniformity and smaller features than silicon wafer foundries could deliver at the time. Not until the 1990s did lithography develop to the point that designers could begin making a case for CMOS imagers again.
- Renewed interest in CMOS was based on expectations of lowered power consumption, camera-on-a-chip integration, and lowered fabrication costs from the reuse of mainstream logic and memory device fabrication.



Teledyne DALSA CCD (left) and CMOS (right) image sensors

Infrared Sensor

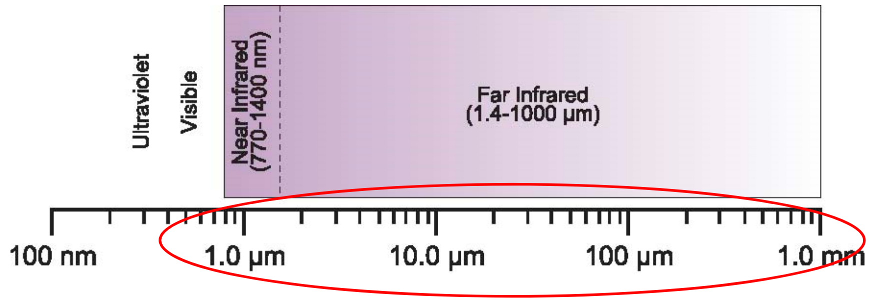


Fig. 1.5 The infrared spectrum.

Infrared light contains the least amount of energy per photon of any other band. Because of this, an infrared photon often lacks the energy required to pass the detection threshold of a quantum detector. Infrared is usually measured using a thermal detector such as a thermopile, which measures temperature change due to absorbed energy.

While these thermal detectors have a very flat spectral responsivity, they suffer from temperature sensitivity, and usually must be artificially cooled. Another strategy employed by thermal detectors is to modulate incident light with a chopper. This allows the detector to measure differentially between the dark (zero) and light states.

Quantum type detectors are often used in the near infrared, especially below 1100 nm. Specialized detectors such as **InGaAs offer excellent responsivity from 850 to 1700 nm**. Typical silicon photodiodes are not sensitive above 1100 nm. These types of detectors are typically employed to measure a known artificial near-IR source without including long wavelength background ambient.

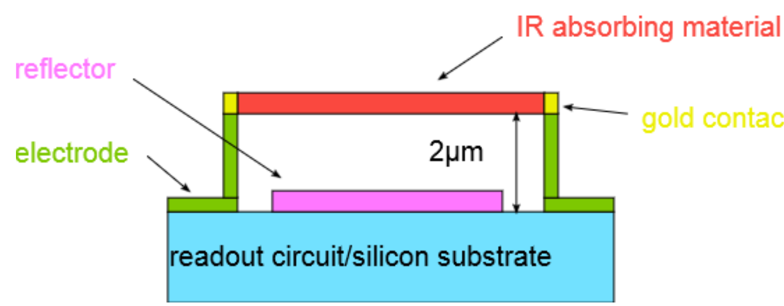
Since **heat is a form of infrared light, far infrared detectors are sensitive to environmental changes** - such as a person moving in the field of view. **Night vision** equipment takes advantage of this effect, amplifying infrared to distinguish people and machinery that are concealed in the darkness.

Infrared is unique in that it exhibits primarily wave properties. This can make it much more difficult to manipulate than ultraviolet and visible light. Infrared is more difficult to focus with lenses, refracts less, diffracts more, and is difficult to diffuse. Most radiometric IR measurements are made without lenses, filters, or diffusers, relying on just the bare detector to measure incident irradiance.

Microbolometer

A microbolometer is a specific type of bolometer used as a detector in a thermal camera. Infrared radiation with wavelengths between 7.5-14 μm strikes the detector material, heating it, and thus changing its electrical resistance. This resistance change is measured and processed into temperatures which can be used to create an image. Unlike other types of infrared detecting equipment, microbolometers do not require cooling

A microbolometer consists of an array of pixels, each pixel being made up of several layers. IR absorbing material (resistor), electrode contacts and bottom layer consists of a silicon substrate and a readout integrated circuit (ROIC).



The quality of images created from microbolometers has continued to increase. The microbolometer array is commonly found in two sizes, 320×240 pixels or less expensive 160×120 pixels. Current technology has led to the production of devices with 640×480 or 1024x768 pixels.

Thermoelectric effect

The thermoelectric effect is the direct conversion of temperature differences to electric voltage and vice versa. A thermoelectric device creates voltage when there is a different temperature on each side. Conversely, when a voltage is applied to it, it creates a temperature difference. At the atomic scale, an applied temperature gradient causes charge carriers in the material to diffuse from the hot side to the cold side.

Thermopile

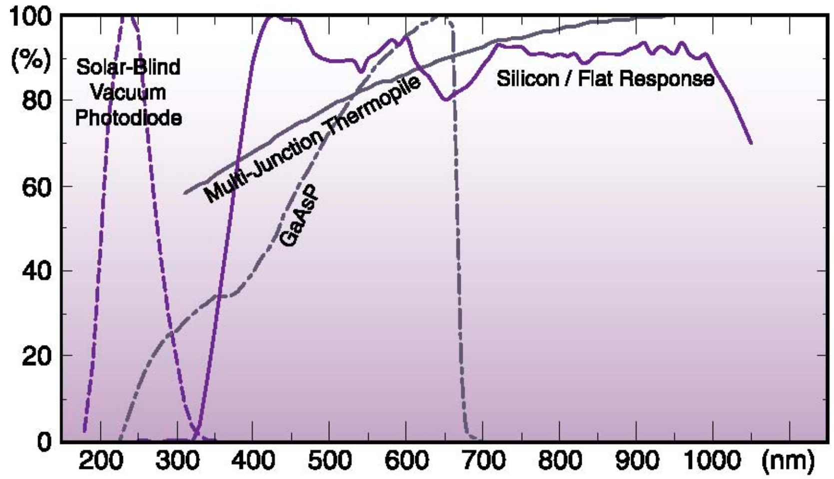
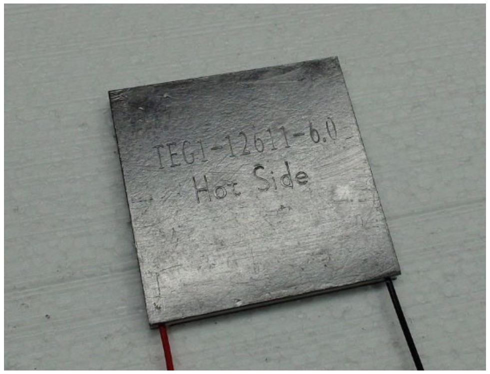


Fig. 10.4 Responsivities: Vac. photodiode, Si / flat response, GaAsP, & Thermopile



The thermopile is a heat sensitive device that measures radiated heat.

The sensor is usually sealed in a vacuum to prevent heat transfer except by radiation. A thermopile consists of a number of thermocouple junctions in series which convert energy into a voltage using the Peltier effect. Thermopiles are convenient sensor for measuring the infrared, because they offer adequate sensitivity and a flat spectral response in a small package. More sophisticated bolometers and pyroelectric detectors need to be chopped and are generally used only in calibration labs.

Thermopiles suffer from temperature drift, since the reference portion of the detector is constantly absorbing heat. The best method of operating a thermal detector is by chopping incident radiation, so that drift is zeroed out by the modulated reading.

The quartz window in most thermopiles is adequate for transmitting from 200 to 4200 nm, but for long wavelength sensitivity out to 40 microns, Potassium Bromide windows are used.

Seeback Coefficient

The Seebeck effect is a classic example of an electromotive force (emf) and leads to measurable currents or voltages in the same way as any other emf. Electromotive forces modify Ohm's law by generating currents even in the absence of voltage differences (or vice versa); the local current density is given by

$$J = \sigma(-\nabla V + E_{emf})$$

Where V is the local voltage and σ is the local conductivity. In general the Seebeck effect is described locally by the creation of an electromotive field

$$\Rightarrow \quad E_{emf} = -S\nabla T$$

Where S is the Seeback coefficient , a property of local material and ∇T is the gradient temperature T.

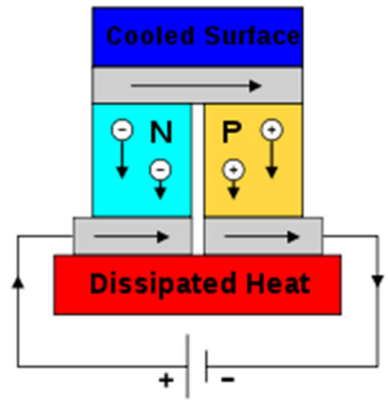
Peltier Effect

The Peltier effect is the presence of **heating or cooling at an electrified junction of two different conductors** and is named for French physicist Jean Charles Athanase Peltier, who discovered it in 1834. When a current is made to flow through a junction between two conductors A and B, heat may be generated (or removed) at the junction. **The Peltier heat generated at the junction per unit time, t , is equal to**

$$\dot{Q} = (\Pi_A - \Pi_B)I$$

Where Π_A *and* Π_B are the Peltier coefficients (how much heat is carried per unit charge) at A and B and I is current. Note that the total heat generated at the junction is not determined by the Peltier effect alone, as it may also be influenced by Joule heating and thermal gradient effects.

if a simple thermoelectric circuit is closed then the Seebeck effect will drive a current, which in turn (via the Peltier effect) will always transfer heat from the hot to the cold junction. The close relationship between Peltier and **Seebeck effects can be seen in the direct connection between their coefficients: *Π* = ST**



The Seebeck circuit configured as a thermoelectric cooler **(Peltier effect)**

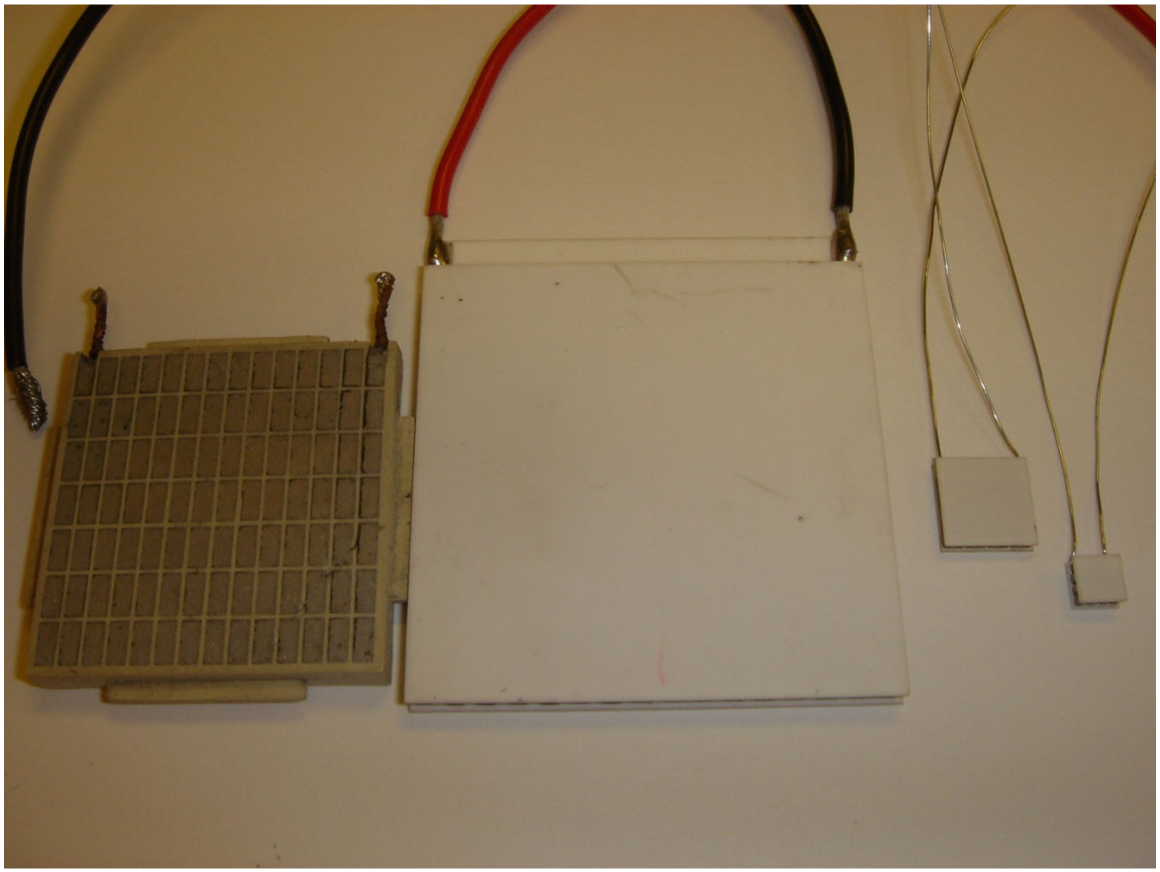
Peltier cells

- Made of crystalline semiconductor materials such as bismuth telluride (Bi_2Te_3) (n-p junctions)
- Peltier Cells are often used for cooling and heating in dual purpose refrigerators,
- Can also be used as sensors and can have output voltages of a few volts (any voltage can be achieved)
- Also used as power generators for small remote installations

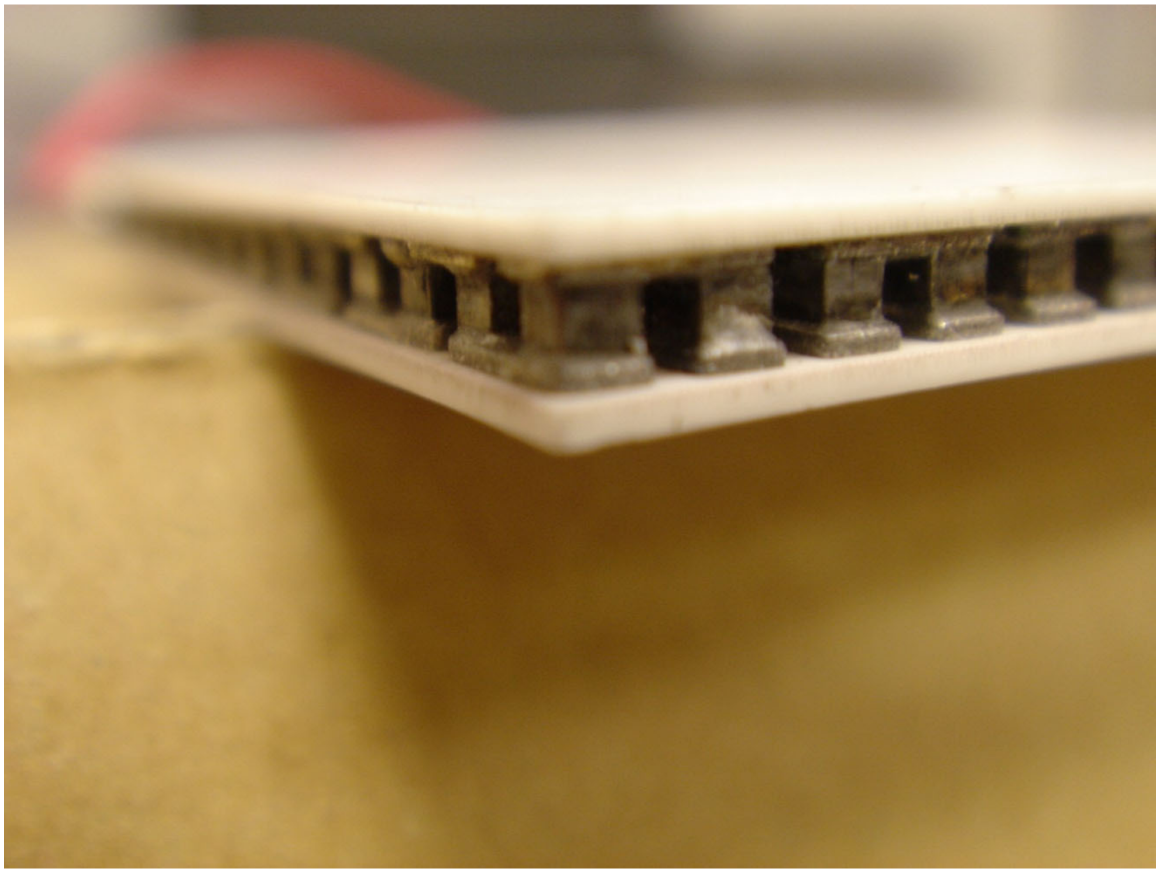
Peltier cells (cont.)

- Junctions are sandwiched between two ceramic plates
- Standard sizes are 15, 31, 63, 127 and 255 junctions
- May be connected in series or parallel, electrically and/or thermally.
- Maximum temperature difference of about 100°C
- Maximum operating temperatures of about 225°C
- Also used as power generators for small remote installations

Some thermopiles (Peltier TEGs)



Details of the TEG construction



Thomson Effect

In many materials, the Seebeck coefficient is not constant in temperature, and so a spatial gradient in temperature can result in a gradient in the Seebeck coefficient. If a current is driven through this gradient then a continuous version of the Peltier effect will occur. This Thomson effect was predicted and subsequently observed by Lord Kelvin in 1851. It describes the heating or cooling of a current-carrying conductor with a temperature gradient.

If a current density J is passed through a homogeneous conductor, the Thomson effect predicts a heat production rate $\dot{q}$ per unit volume of:

$$\dot{q} = -\mathrm{K} J \cdot \nabla T$$

Where ∇T is the temperature gradient and K is **Thomson coefficient** $\boldsymbol{K = T\frac{dS}{dT}}$ This equation however neglects Joule heating, and ordinary thermal conductivity

Full thermoelectric equations

Often, more than one of the above effects is involved in the operation of a real thermoelectric device. The Seebeck effect, Peltier effect, and Thomson effect can be gathered together in a consistent and rigorous way, described here; the effects of Joule heating and ordinary heat conduction are included as well. As stated above, the Seebeck effect generates an electromotive force, $E_{emf} = -S\nabla T$ leading to the **current equation**

$$J = \sigma(-\nabla V + E_{emf}) = \sigma(-\nabla V - S\nabla T)$$

To describe the Peltier and Thomson effects we must consider the flow of energy. To start we can consider the dynamic case where both temperature and charge may be varying with time. ***The full thermoelectric equation for the energy accumulation***,

$$\dot{e} = \nabla \cdot (K\nabla T) - \nabla \cdot (V + \Pi)J + \dot{q_{wxt}}$$

where K is the thermal conductivity. **The first term is the Fourier's heat conduction law, and the second term shows the energy carried by currents. The third term is the heat added from an external source (if applicable)**

In the case where the material has reached a steady state, the charge and temperature distributions are stable so one must have both $\dot{e} = 0$ and $\nabla \cdot J = 0$. Using these facts and the second Thomson relation (see below), the heat equation then can be simplified to

$$-\dot{q_{ext}} = \nabla \cdot (K \nabla T) + J \cdot (\sigma^{-1} J) - TJ \cdot \nabla S$$

The middle term is the Joule heating, and the last term includes both Peltier (∇S at junction) and Thomson (∇S in thermal gradient) effects. Combined with the Seebeck equation for J , this can be used to solve for the steady state voltage and temperature profiles in a complicated system. If the material is not in a steady state, a complete description will also need to include dynamic effects such as relating to electrical capacitance, inductance, and heat capacity.

Thomson relation

In 1854, Lord Kelvin found relationships between the three coefficients, implying that the Thomson, Peltier, and Seebeck effects are different manifestations of one effect (uniquely characterized by the Seebeck coefficient).

The first Thomson relation is $K = \frac{d\Pi}{dT}$ - S,

Where T the absolute temperature**, K is the Thomson coefficient, Π is the Peltier coefficient, and S is the Seebeck coefficient.** This relationship is easily shown given that the Thomson effect is a continuous version of the Peltier effect. Using the second relation (described next), the first Thomson relation becomes $K = T\frac{dS}{dT}$

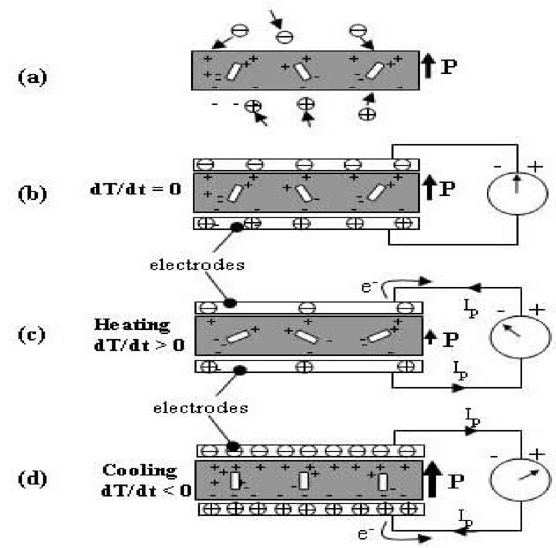
The second Thomson relation is $\Pi = TS$

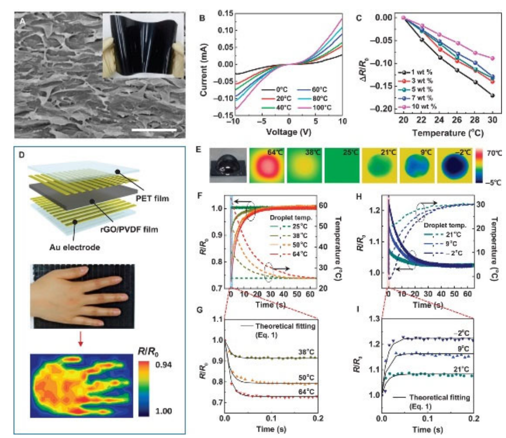
This relation expresses a subtle and fundamental connection between the Peltier and Seebeck effects. It was not satisfactorily proven until the advent of the Onsager relations, and it is worth noting that this second Thomson relation is only guaranteed for a time-reversal symmetric material; if the material is placed in a magnetic field, or is itself magnetically ordered (ferromagnetic, antiferromagnetic, etc.), then the second Thomson relation does not take the simple form shown here.

The Thomson coefficient is unique among the three main thermoelectric coefficients because it is the only one directly measurable for individual materials. The Peltier and Seebeck coefficients can only be easily determined for pairs of materials; hence, it is difficult to find values of absolute Seebeck or Peltier coefficients for an individual material.

Pyroelectric

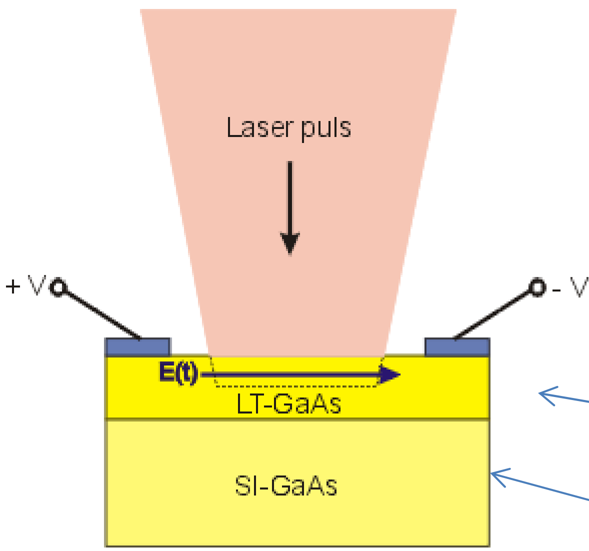
The incident radiation is absorbed in a ferroelectric material which has molecules with a permanent electric dipole moment. The net electric polarization present is temperature dependent (below the a critical temperature characteristic of the material). When configured as a capacitor in a circuit, changes in polarization induced by temperature changes in the material can be detected by measuring the change in the charge on the plates of the capacitor. Pyroelectric detectors can be made with response times in the nanosecond region and with a wavelength response extending out to » 100 ^{1}m. They have proved very useful as low cost, robust IR detectors in such uses as first detection and intruder alarms.





PCA- basic concept

How does a PCA work?



A photoconductive antenna (PCA) for terahertz (THz) waves consists of a highly resistive direct semiconductor thin film with two electric contact pads. The film is made in most cases using a III-V compound semiconductor like GaAs. It is epitaxially grown on a semi-insulating GaAs substrate (SI-GaAs), which is also a **highly resistive material**.

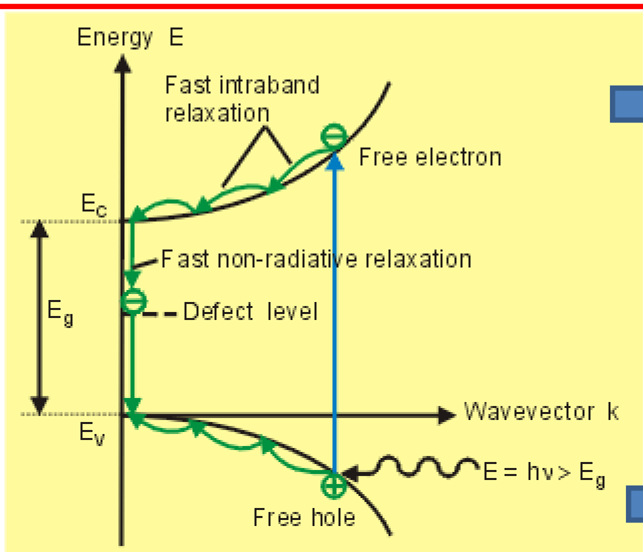
The important difference between the SI-GaAs substrate and the film is **the relaxation time for excited carriers**. In a SI-substrate the carrier lifetime is about 20 ps, but in the **film shorter than 1 ps.**

A short **laser pulse with pulse width < 1 ps** is focused between the electric contacts of the PCA. The photons of the laser pulse have a photon energy **$E = h \cdot \nu$ larger than the energy gap E_g and are absorbed in the film.** Each absorbed photon **creates a free electron in the conduction band and a hole in the valence band of the film and makes them for a short time electrical conducting until the carriers are recombined.**

PCA can be used as THz **transmitter** as well as THz **receiver**

In case of a **transmitter** a voltage V is connected on the electrical contacts and the excited **carriers are accelerated by the electric field during the optical pulse**, which results in a short broadband electromagnetic pulse with a time-dependent electrical field E(t) and frequencies in the THz region.

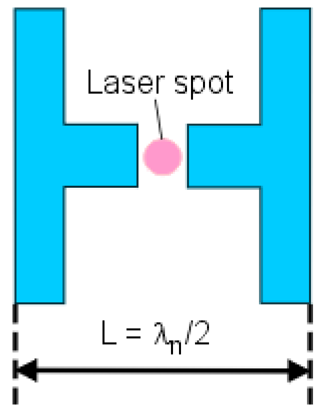
In case of a **receiver** a current amplifier is connected on the electrical contacts. **During the optical pulse** the **excited carriers are accelerated by the electric field component of the incident terahertz pulse** with the time-dependent electrical field E(t). This leads to a measurable current signal in the outer circuit.



To get the needed **short carrier lifetime**, the film must **include crystal defects**. These defects can be created by ion implantation after the film growth or alternatively by a low temperature growth. Low temperature grown GaAs (LT-GaAs) between 200 and 400 °C contains **excess arsenic clusters.**

These clusters create defect levels within the band gap E_g and lead to a **fast non-radiative recombination of the electron-hole pairs within a time interval** < 1 ps

PCA



The photoconductive antenna can be considered as a dipole of the length L, which is in resonance with the electromagnetic wavelength l_n inside the semiconductor.
The resonance condition is $L = m \cdot \lambda_n/2$ with m = 1, 2, 3,..- integer.
The wavelength λ_n in the material with the refractive index n is given by $\lambda_n = \lambda/n$. Using the wave relation $c = \lambda \cdot f$ and m = 1, the resonance frequency of the antenna f is given by $f = c/(2\times n\times L)$
with
$c = 3\times10^8$ m/s - speed of light in the vacuum
n - refractive index of the semiconductor antenna material
L - length of the antenna.

PCA

The refractive index n of GaAs at terahertz frequencies is n = 3.4. With this value the first resonant frequency and wavelength of the antenna with the length L can be calculated as follows:

f (THz)	λ (µm)	L (µm)
0.3	1000	147
0.5	600	88
1.0	300	44
1.5	200	29.4
3.0	100	14.7

Broadband

Dipole:
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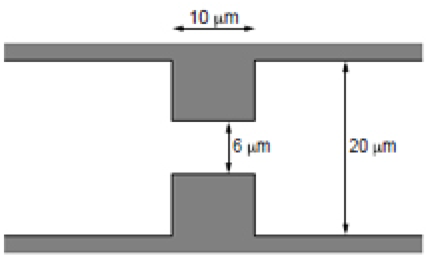
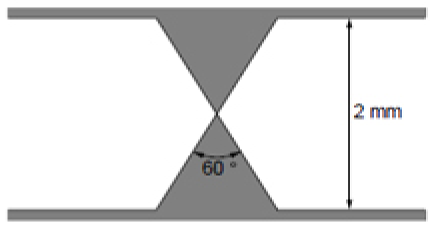
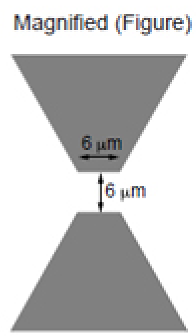


Bow-Tie:
G10620-12





Spiral:
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