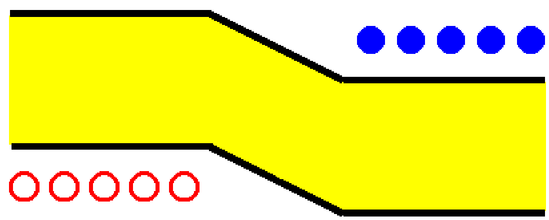
Optical Detectors

Wei-Chih Wang
Department of Mechanical Engineering
University of Washington
ME557

Semicoductor types (interval photoemission)



P-N junction (no bias, short circuit)

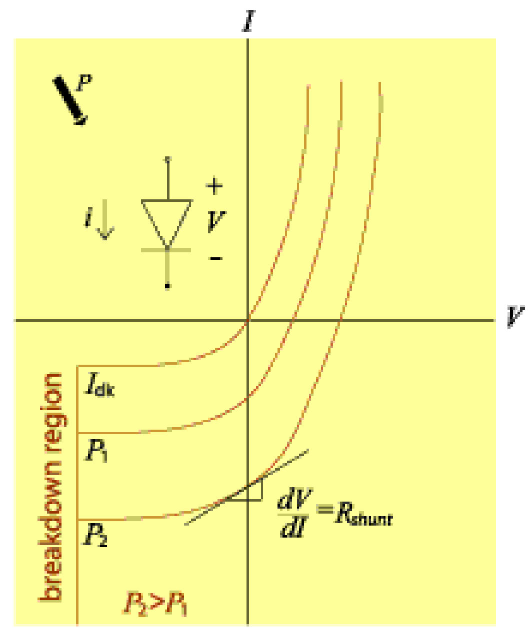
1. Absorbed hv excited e from valence to conduction, resulting in the creation of e-h pair
2. Under the influence of a bias voltage these carriers move through the material and induce a current in the external circuit.
3. For each electron-hole pair created, the result is an electron flowing in the circuit.

Photodiode Operation

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

$$I = I_p + I_{dk}\left(e^{qV_0/kT} - 1\right)$$

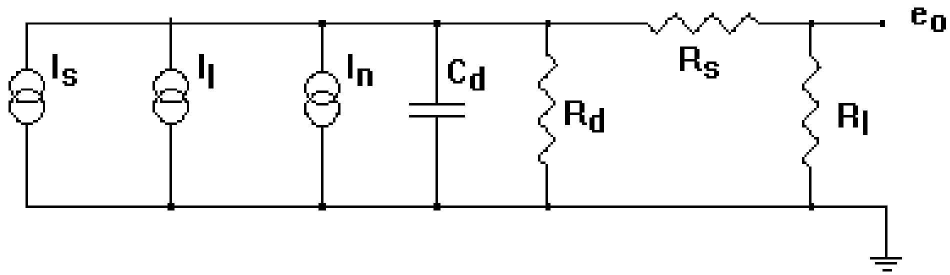
where I is the total device current, I_p is the photocurrent, I_{dk} is the dark current (leakage current), V_0 is the voltage across the diode junction, q is the charge of an electron, k is Boltzmann's constant, and T is the temperature in degrees Kelvin.



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 $V = 0$.

Equivalent Operating Circuits

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

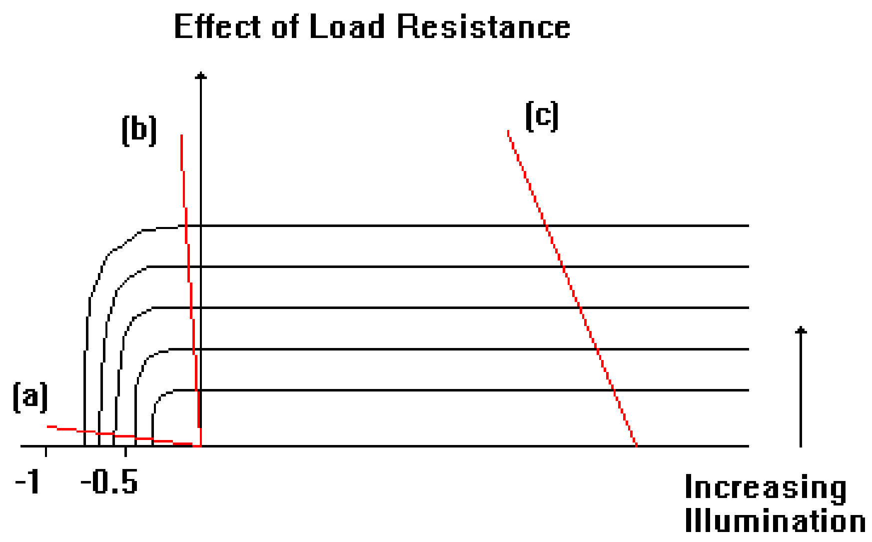


I_s = signal current
I_l = leakage current
I_n = noise current
C_d = diode junction capacity

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

$$e_o = \left[I_s + I_l + I_n \right] \left[R_l \, R_d \right] / \left[R_l + R_d + R_s \right]$$

Fundamentally a photodiode is a current generator. The junction capacitance of the photodiode depends on the depletion layer depth and hence bias voltage. The value of the shunt resistance Rd is usually high (megohms). The series resistance Rs is low. The effect of the load resistor Rl value on the current/voltage characteristics is shown in the following figure:



(a) Photovoltaic Operation - Rl>>Rd, load line
(b) Zero Bias Operation - Rl<<Rd, load line
(c) Photoconductive Operation - load line

Types of Optical Detectors

Photon detectors may be further subdivided according to the physical effect that produces the detector response. Some important classes of photon detectors are listed below.

•*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.

•*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.

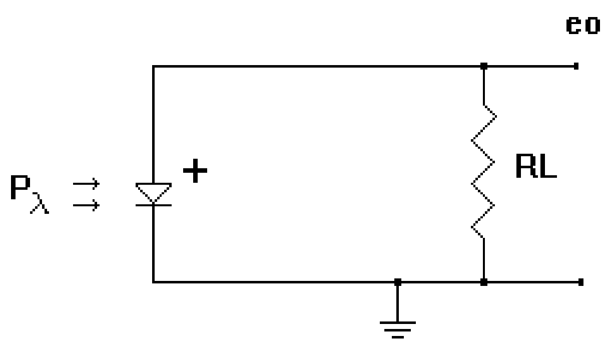
•*Photoemissive*. These detectors are based on the photoelectric effect, in which incident photons release electrons from the surface of the detector material. The free electrons are then collected in an external circuit.

Photovoltaic

(a) Photovoltaic Operation - Rl>>Rd, load line

The generated photocurrent flows through Rd causing a voltage across the diode. This voltage opposes the band gap potential of the photodiode junction, forward biasing it. The value of Rd drops exponentially as the illumination increases. Thus the photo-generated voltage is a logarithmic function of incident light intensity. The major disadvantage of this circuit is that the signal depends on Td, which typically has a wide spread of values over different production batches. The basic circuit is shown below:

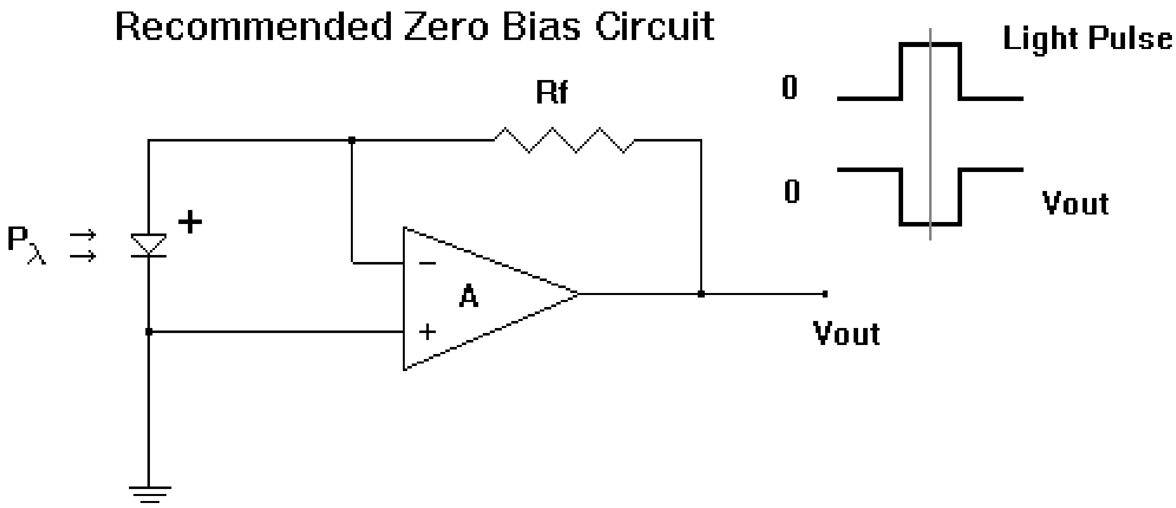
Basic Photovoltaic Circuit



Zero Bias Operation

(b) Zero Bias Operation Vo=0 - Rl<<Rd, load line

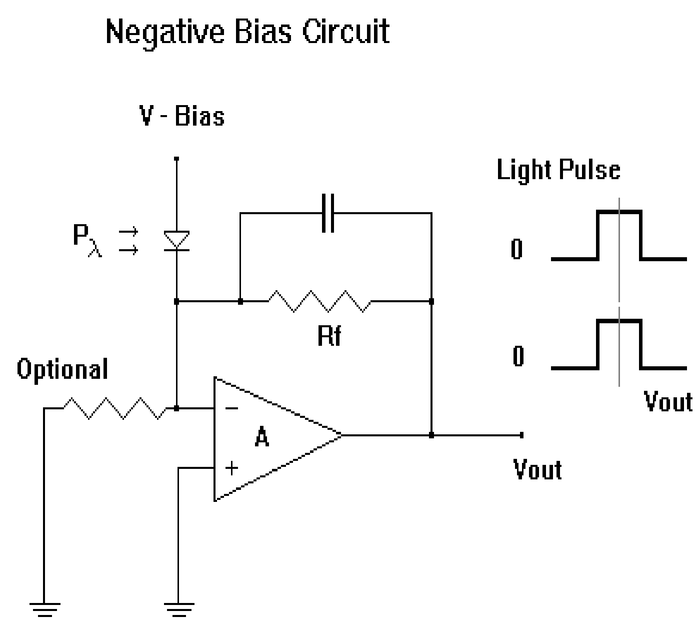
The generated photocurrent flows through Rl which is fixed. The resultant voltage is therefore linearly dependent on the incident radiation level. One way to achieve sufficiently low load resistance, and an amplified output voltage, is by feeding the photocurrent to an operational amplifier virtual ground as shown below. The circuit has <u>a linear response and has low noise due to the almost complete elimination of leakage current</u>.

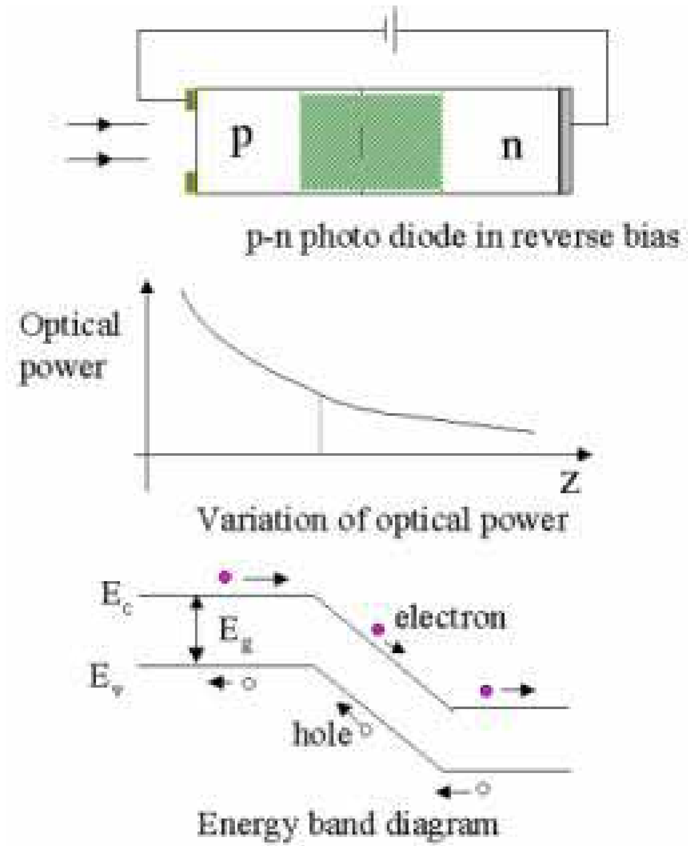


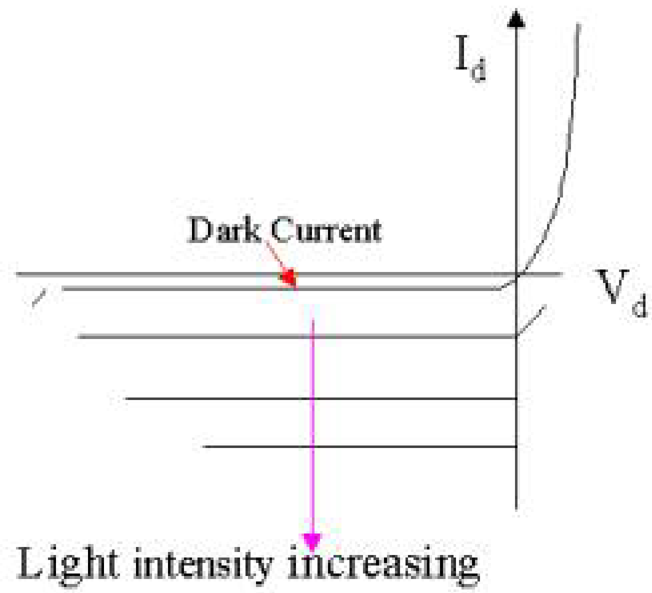
w.wang

Photoconductive

(c) Photoconductive Operation - load line
In the photoconductive mode, the generated photocurrent produces a voltage across a load resistor in parallel with the shunt resistance. Since, in the reverse biased mode Rd is substantially constant, large values of Rl may be used still giving a linear response between output voltage and applied radiation intensity. This form of circuit is required for high speed of response. The main disadvantage of this mode of operation is the increased leakage current due to the bias voltage, giving higher noise than the other circuit modes already described. (Note that the photodiode is reverse-biased.)





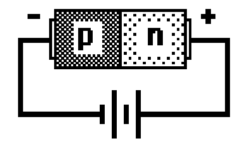


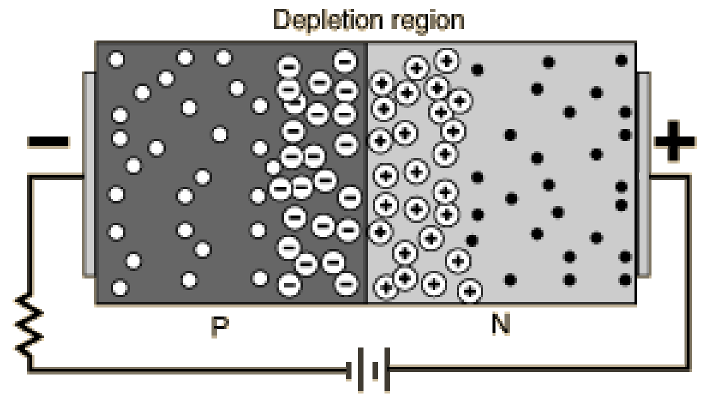
Reverse bias characteristic

- 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

w.wang

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.





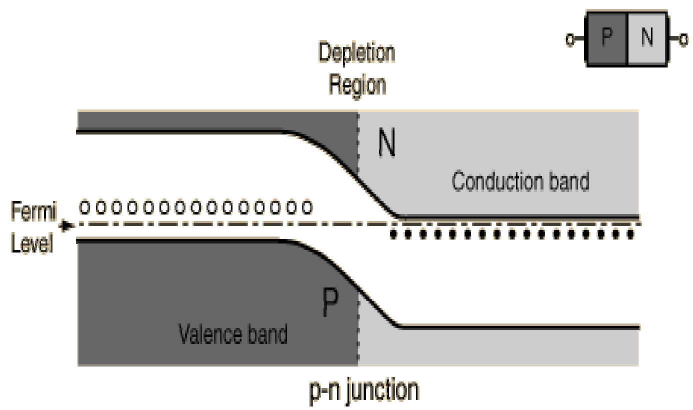
V_A

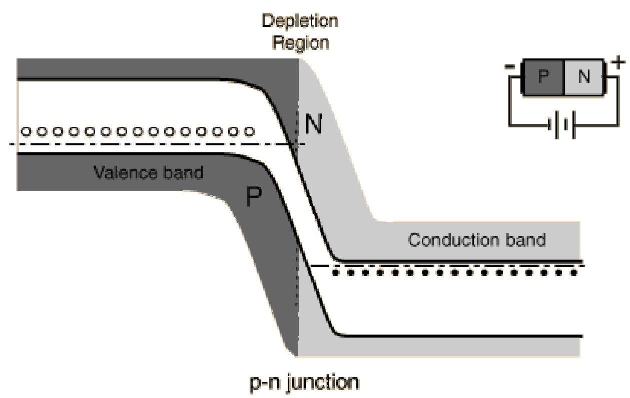
Depletion region width:

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

$$I \sim I_{sat}$$

Reverse Bias





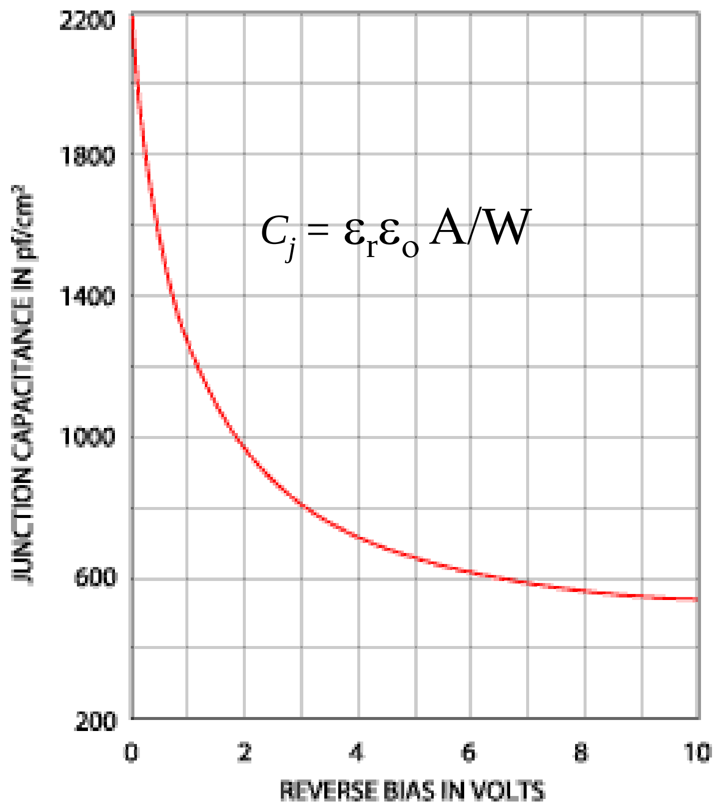
To reverse-bias the p-n junction, the p side is made more negative, making it "uphill" for electrons moving across the junction. The conduction direction for electrons in the diagram is right to left, and the upward direction represents increasing electron energy.

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 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, which varies with applied bias, as shown in the graph below. Therefore, it is common to specify the junction capacitance at zero external bias.

w wang

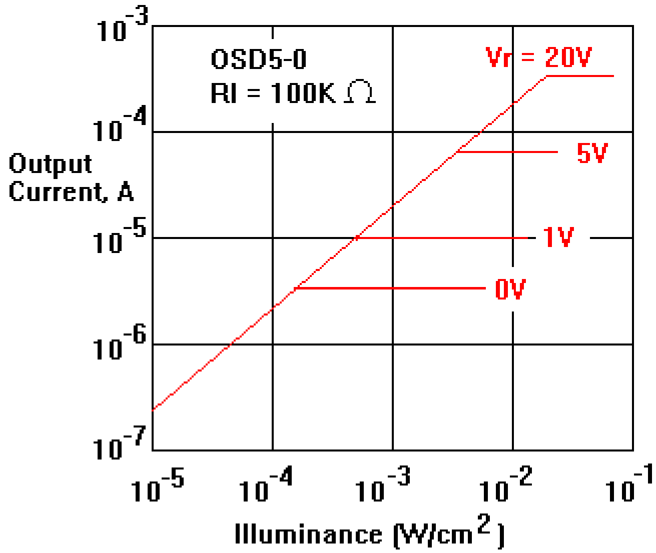


$$C_j = \varepsilon_r \varepsilon_o A/W$$

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

Linearity

The output of photodiode when reverse-biased is extremely linear with respect to the illuminance applied to the photodiode junction, as shown in the graph.



$I \sim I_p - I_{sat}$

Effect of Reverse Bias on Photodiode Linearity

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).

Response time

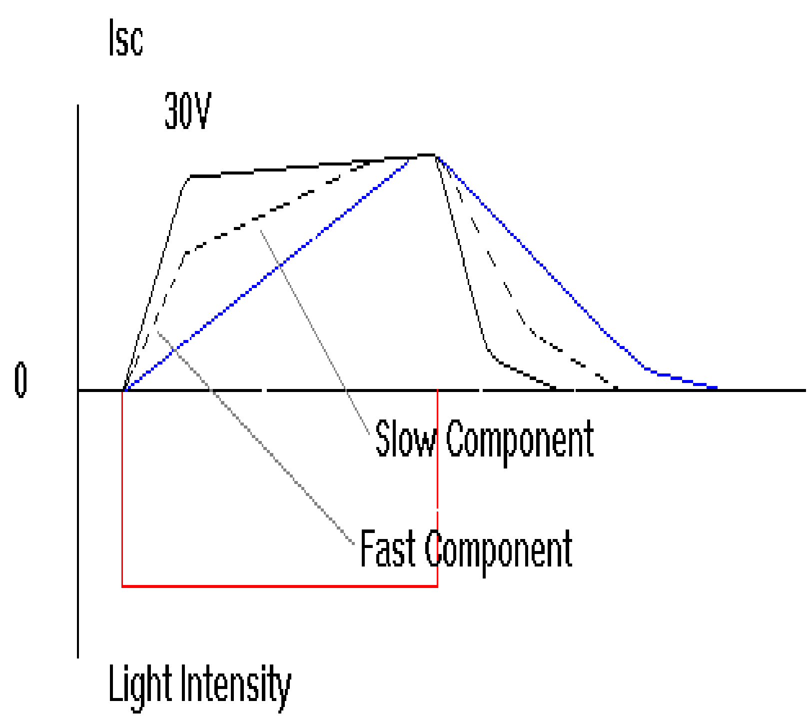
The time required for the detector to respond to an optical input. The response time is related to the bandwidth of the detector by

$$BW = 0.35/t_r$$

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.

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.

Quantum efficiency

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

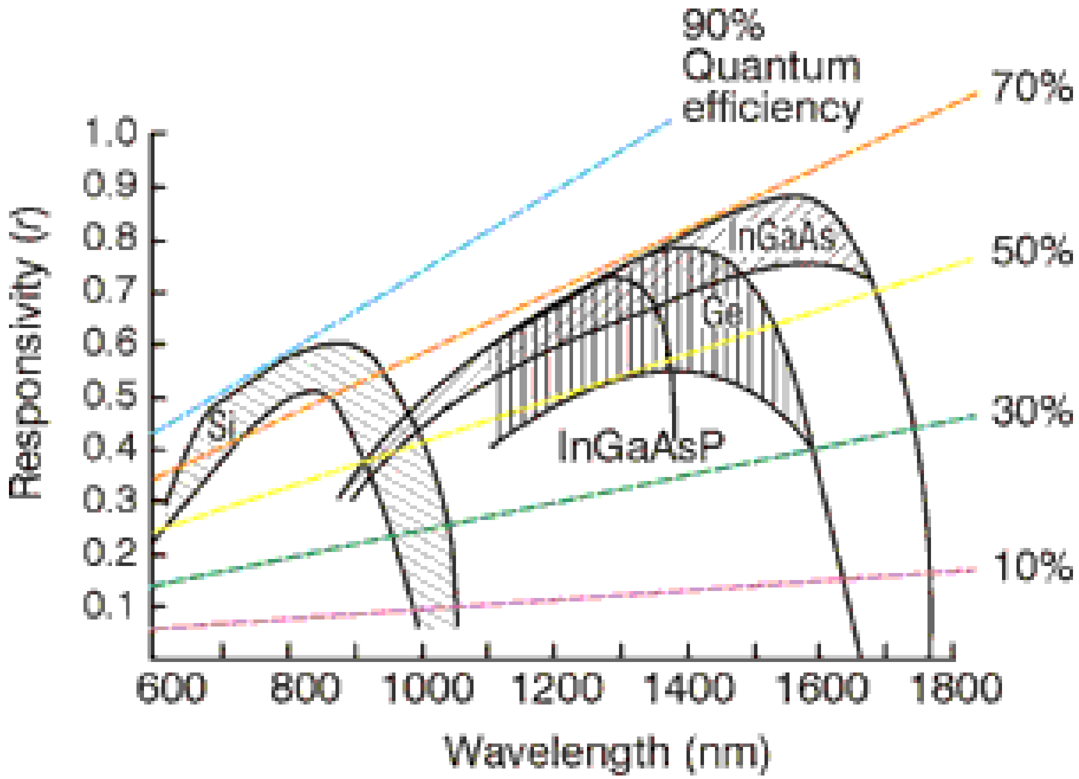
Responsivity R_λ is defined as the ratio of radiant energy (in watts), P, incident on the photodiode to the photocurrent output in amperes I_p. It is expressed as the absolute responsivity in amps per watt. Please note that radiant energy is usually expressed as watts/cm^2 and that photodiode current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

Photodetectors



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

Electron rate then

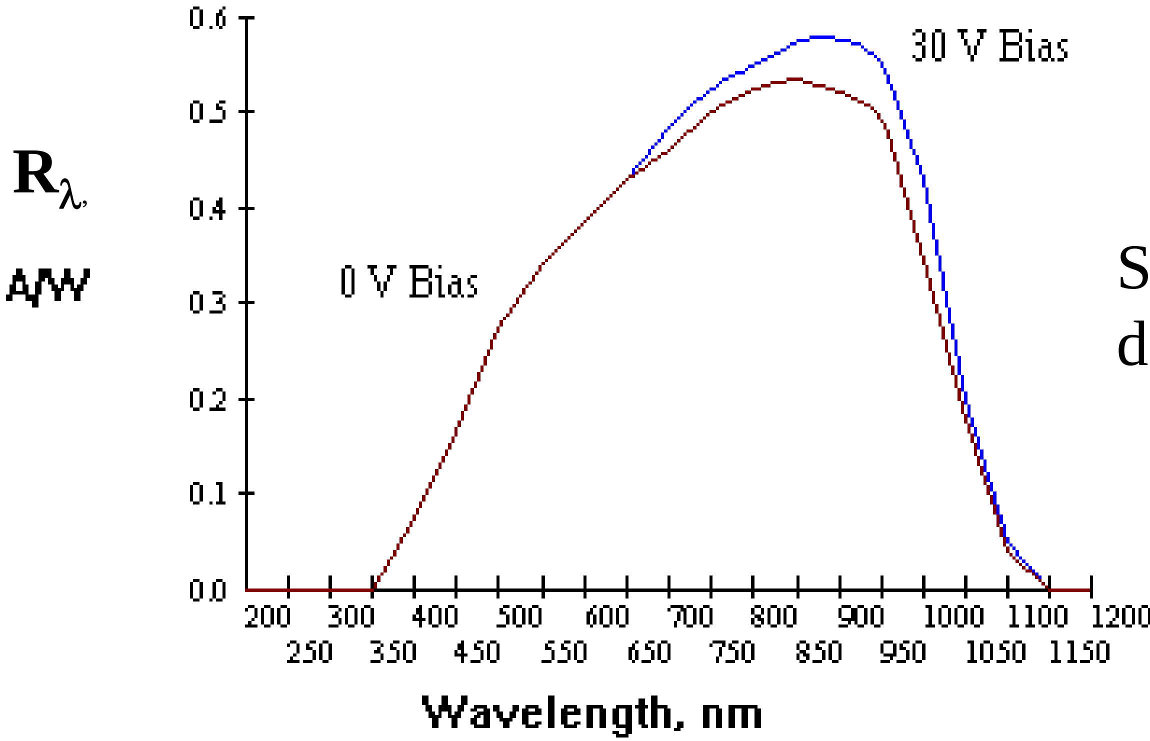
$$r_e = \eta r_p = \eta P/(h\nu)$$

Therefore, the output photo current is

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

The responsivity may then be written

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



Silicone based detector

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

Detector Angular Respons

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:

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

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

Temperature Effects

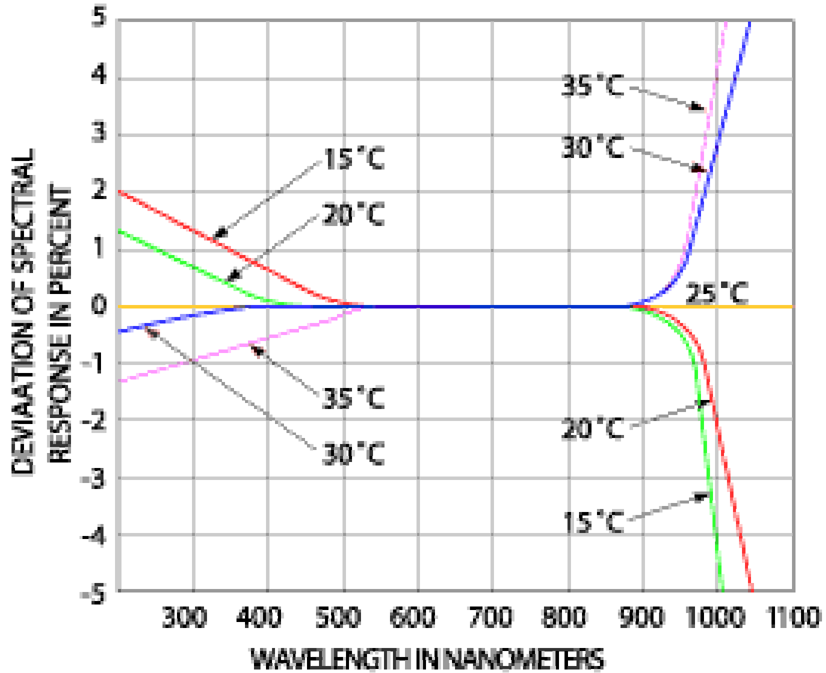
Typically, the dark current of a PNN+ silicon photodiode approximately doubles for each 10°C increase or decrease in the device temperature. The shunt resistance approximately doubles for each 6°C change:

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

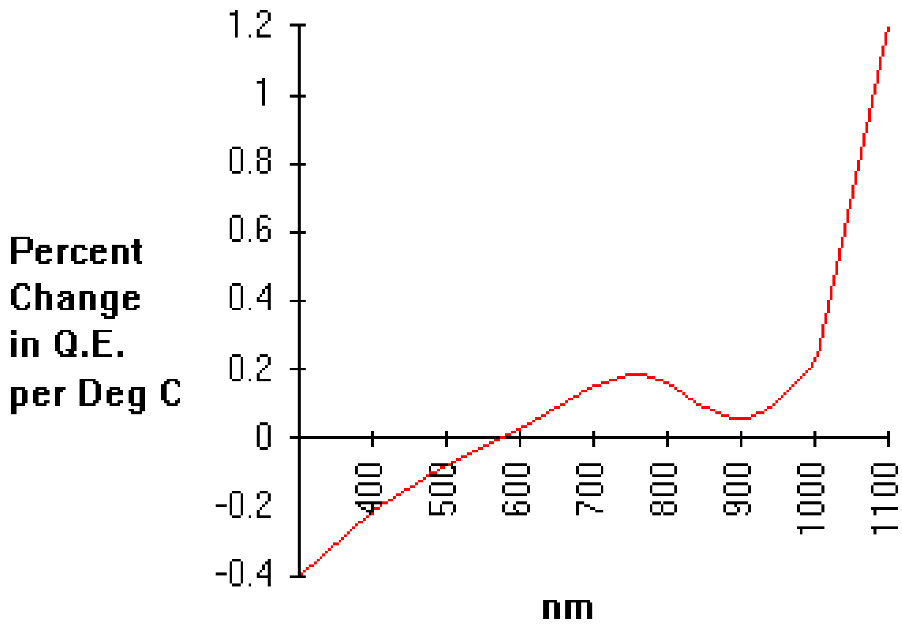
$$R_{shunt}(T_2) = R_{shunt}(T_1) \cdot 2^{\frac{(T_2 - T_1)}{6}}$$

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

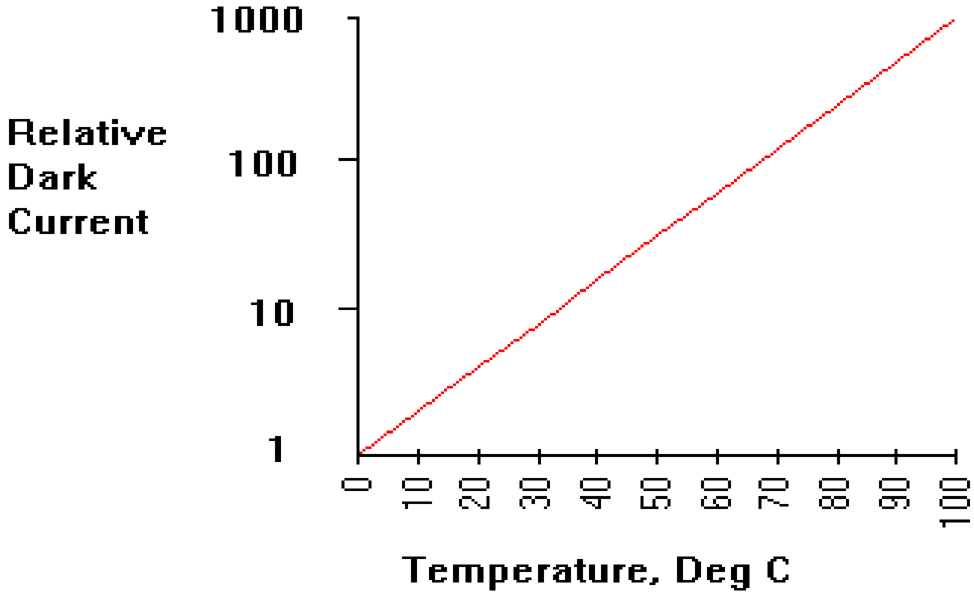


Temperature Dependence of Q.E.

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 absorbtion of the device. Q.E. values shift lower in the UV region and higher in the IR region.

w.wang

Temperature Effects



Dark Current vs Temperature

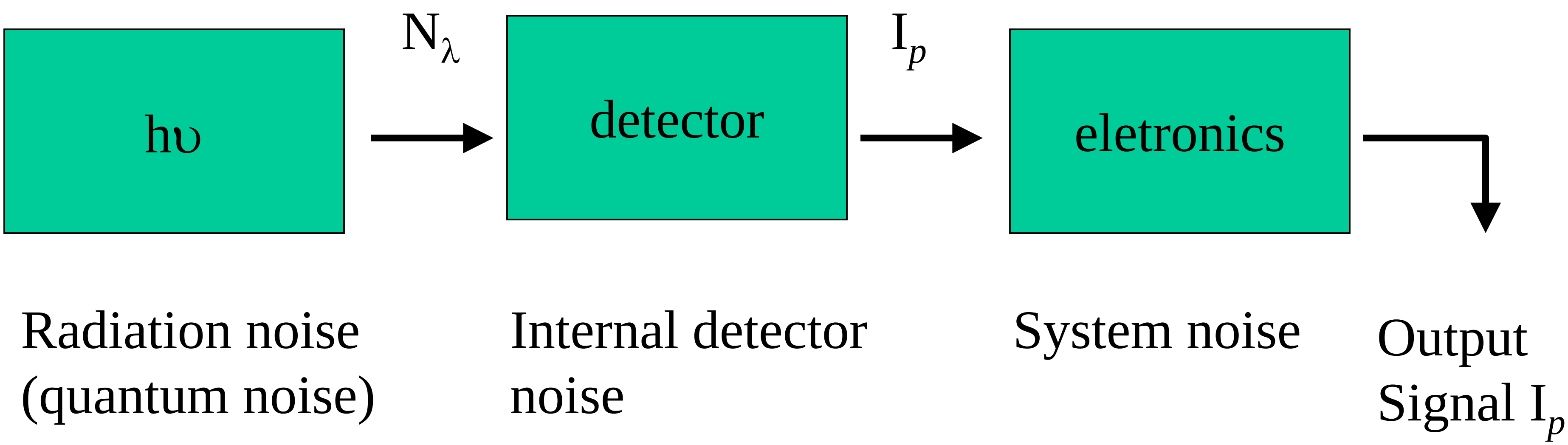
The second change is caused by exponential increases in the thermally excited electron-hole pairs resulting in increasing dark current. This leakage doubles for each 8 to 10 deg C temperature increase

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)

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 the shunt resistance of the device, series resistance and the load resistance. The Johnson noise (thermal noise) is given by:

Johnson Noise Equation

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

Where: I_j = Johnson noise current

K = Boltzmann constant (1.38×10 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,

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

$i_d^2 = 2eBI_d$ „white noise"

With light: $i_d^2 = 2eBI_p$

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

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

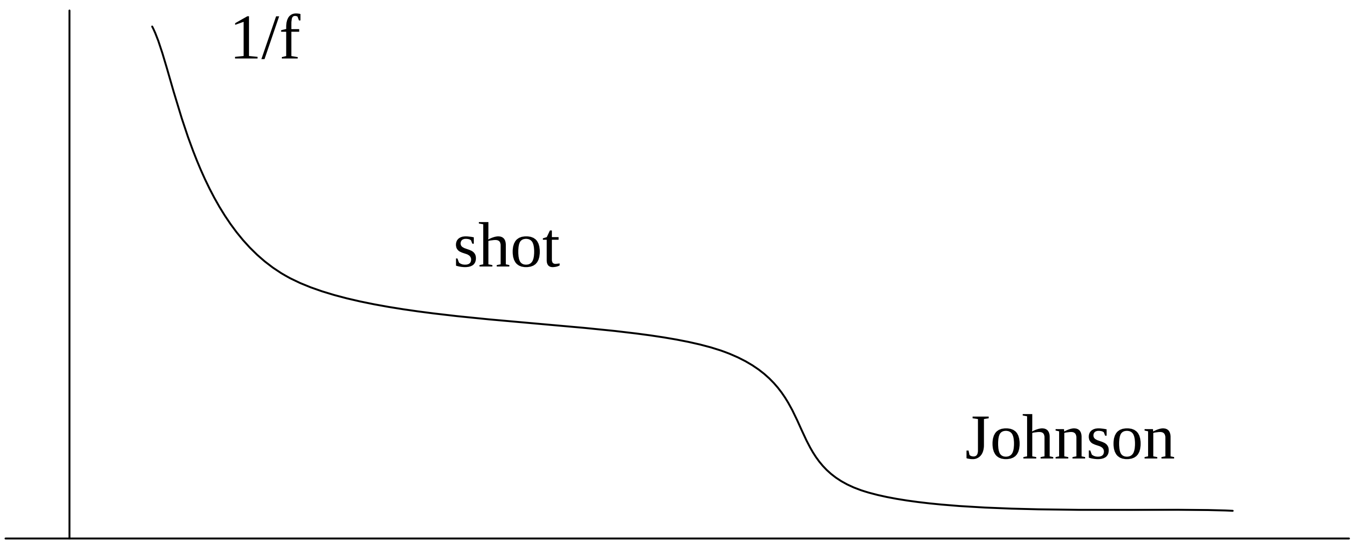
Usually very smaller than shot noise except at very low frequency

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 5E8 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

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.

p-i-n Photodiodes

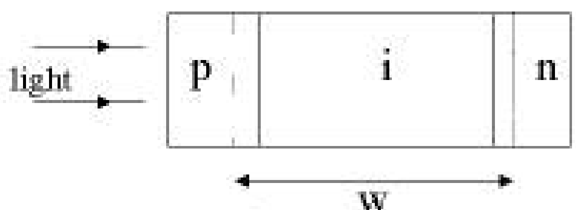
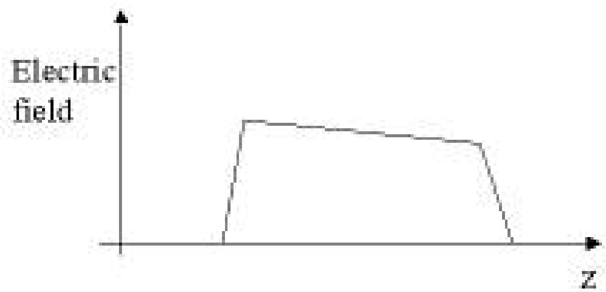


Fig. Device structure



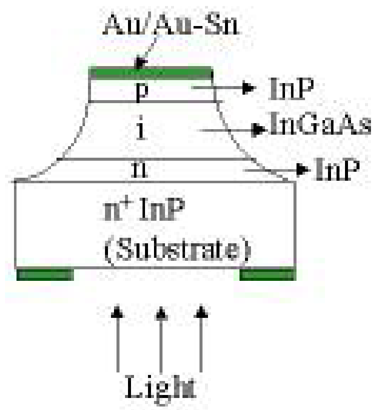
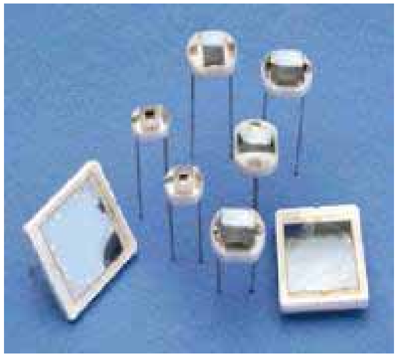


Fig. Fabrication structure

Mim Lal Nakarmi, KSU

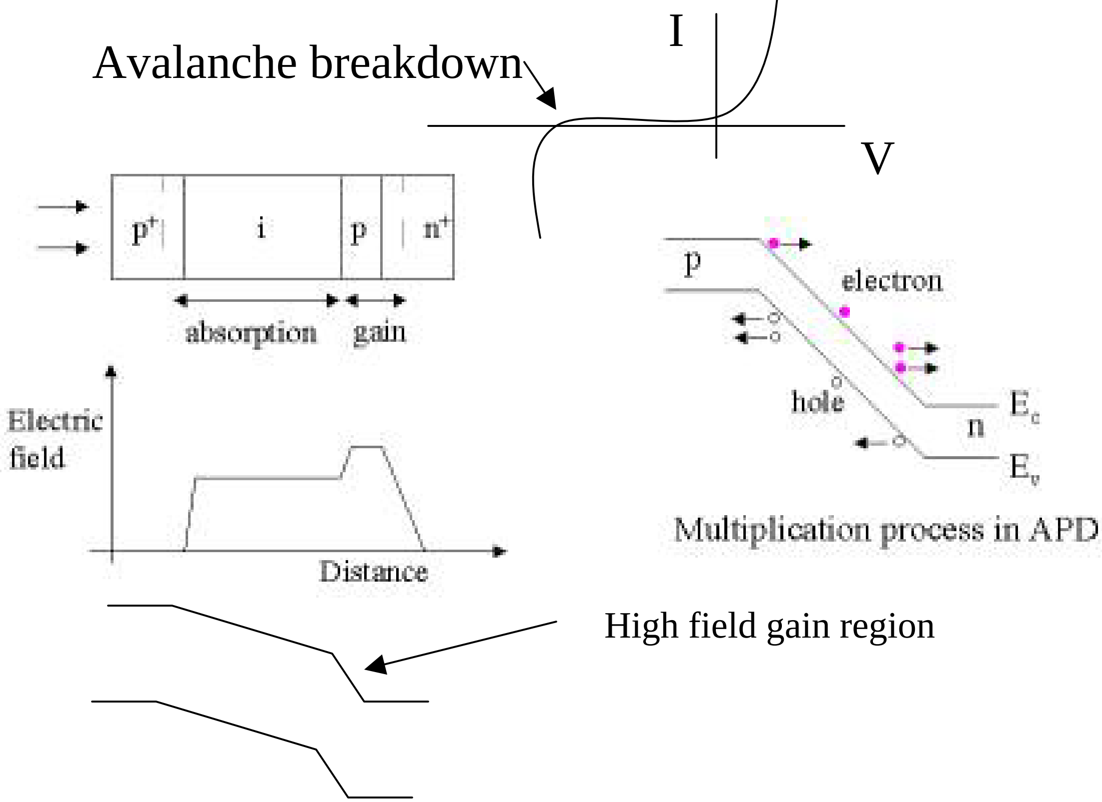


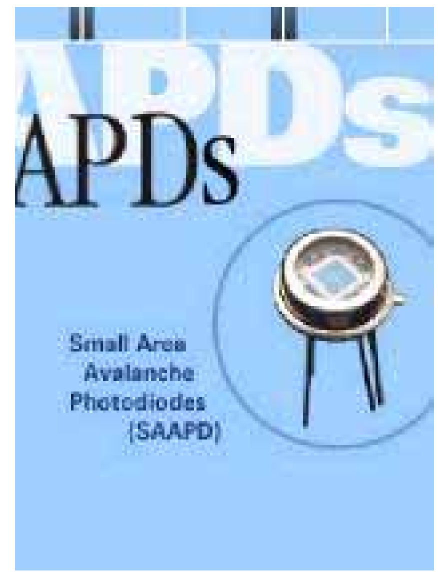
-As mentioned- increasing deletion layer width improve quantum coefficient
=> Lower doping increase deletion width

w.wang

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

Avalanche Photodiodes (APD)

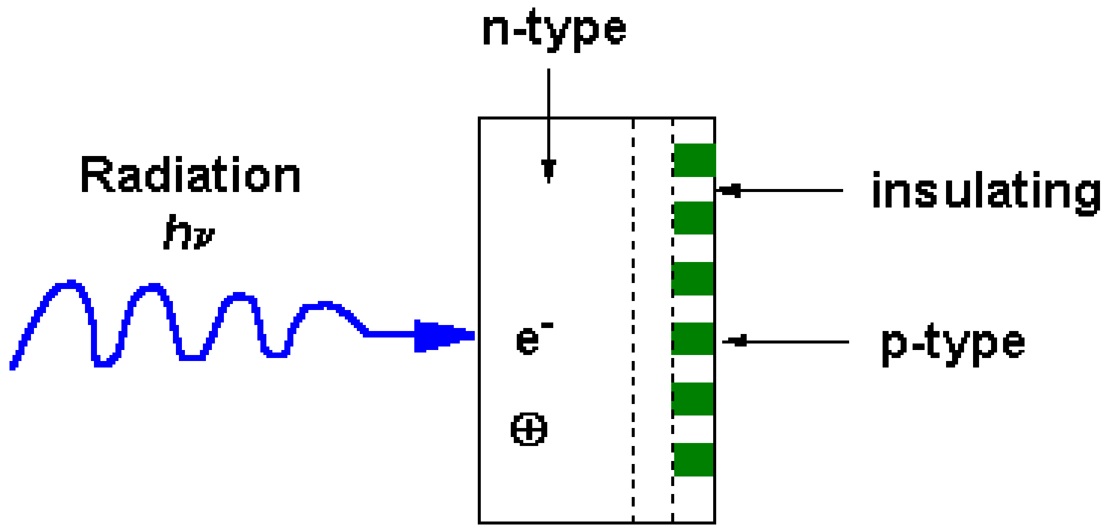




Mim Lal Nakarmi, KSU

- 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)

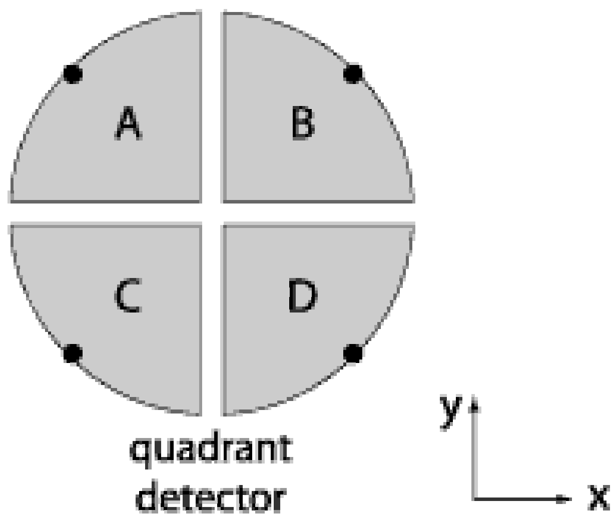


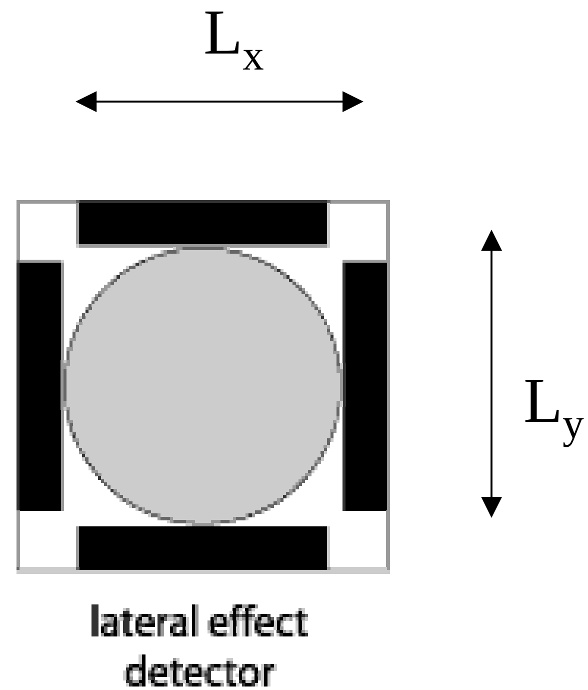
A photodiode array (PDA) is a linear array of discrete photodiodes on an integrated circuit (IC) chip. For spectroscopy it is placed at the image plane of a spectrometer to allow a range of wavelengths to be detected simultaneously. In this regard it can be thought of as an electronic version of photographic 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





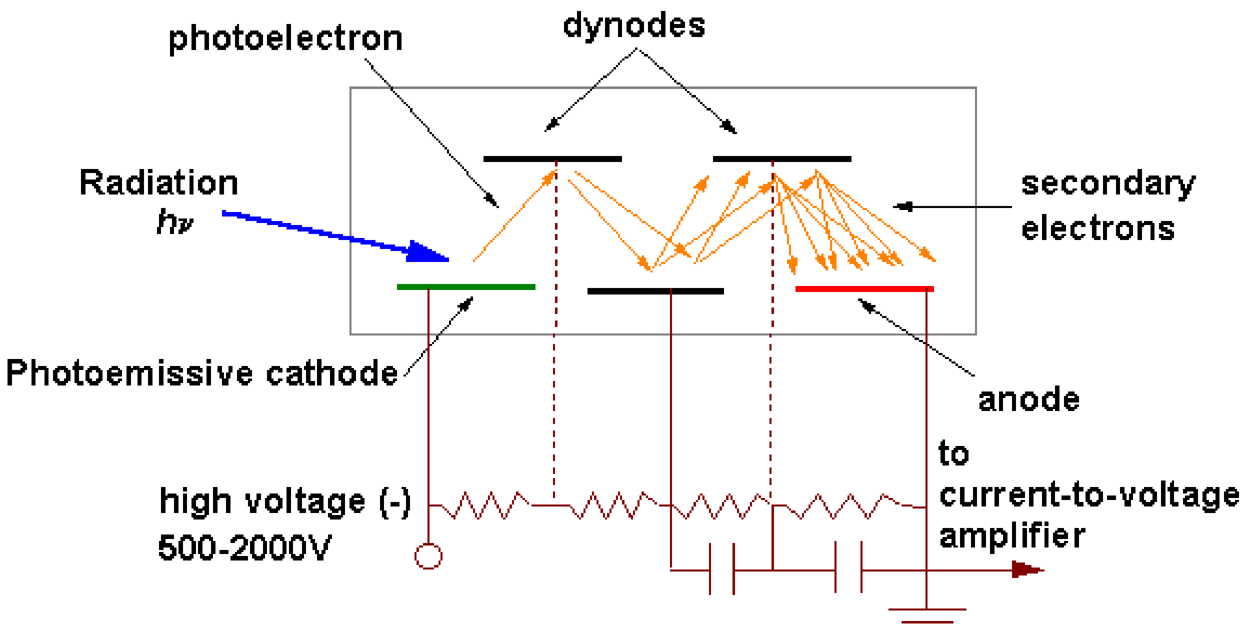
$$x = \frac{(b+d)-(a+c)}{a+b+c+d}$$

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

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

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

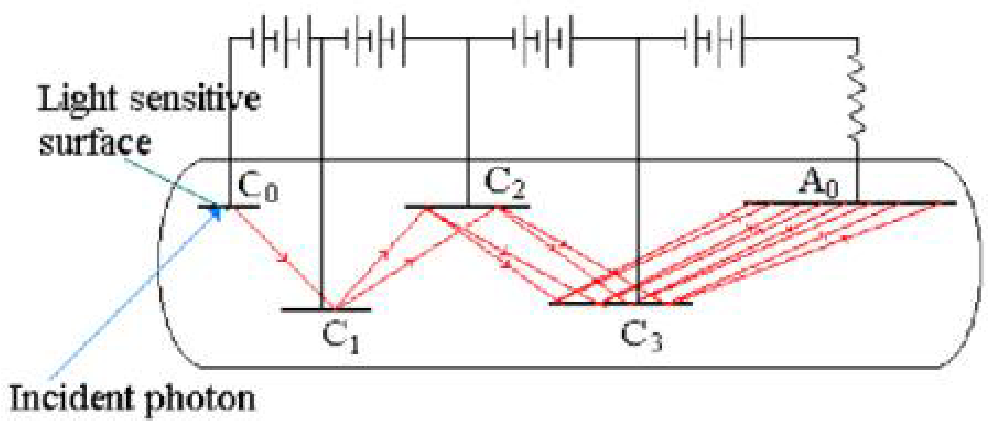
Photomultiplier Tubes (PMTS)



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.

w.wang

Photomultiplier Tubes

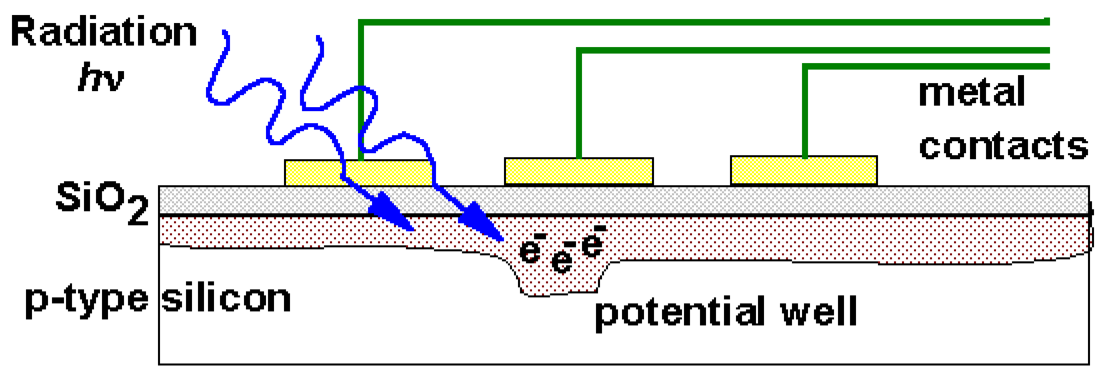


Mim Lal Nakarmi, KSU

Secondary emission of electrons due to high velocity electrons

- Amplification is very high
- Used in single photon counter

Charge coupled detector array (CCD)



A CCD is an integrated-circuit chip that contains an array of capacitors 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.

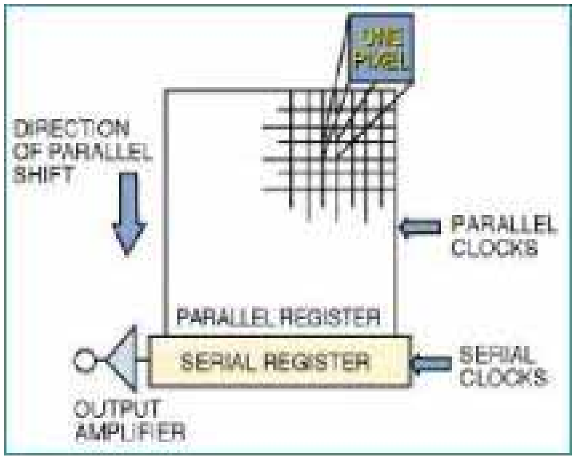
Charge Coupled Device was invented in the late 1960s by researchers at Bell Labs,
The CCD's superb ability to detect light has turned it into the industry-standard image sensor technology.

CCD Basics

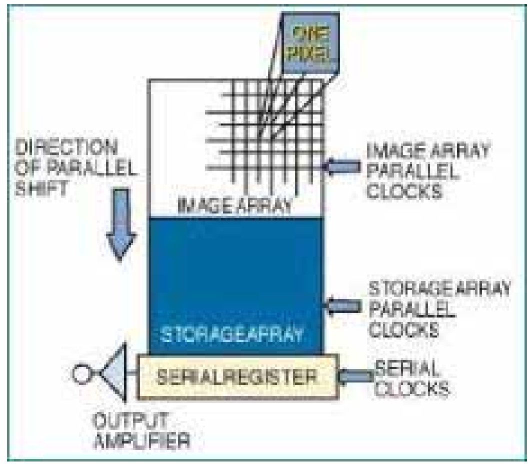
CCD imaging is performed in a three-step process:

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.

CCD architectures

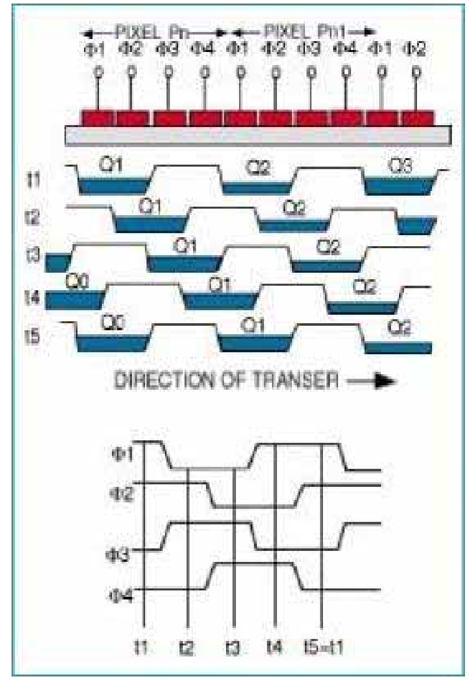


In a full-frame CCD, the exposure is controlled by a mechanical shutter or strobe. The resultant charges are shifted one row at a time to serial register. After a row is read out by the serial register next row is shifted to the register for read out. The process is repeated until all rows are transferred, at which point the array is ready for the next exposure.



Frame Transfer

In a frame-transfer CCD, the entire array is shifted quickly to an identically sized storage array. The read out process from the storage array is the same as in a full-frame device, but the frame rates are increased because the image array can begin the next exposure while the readout process is taking place.

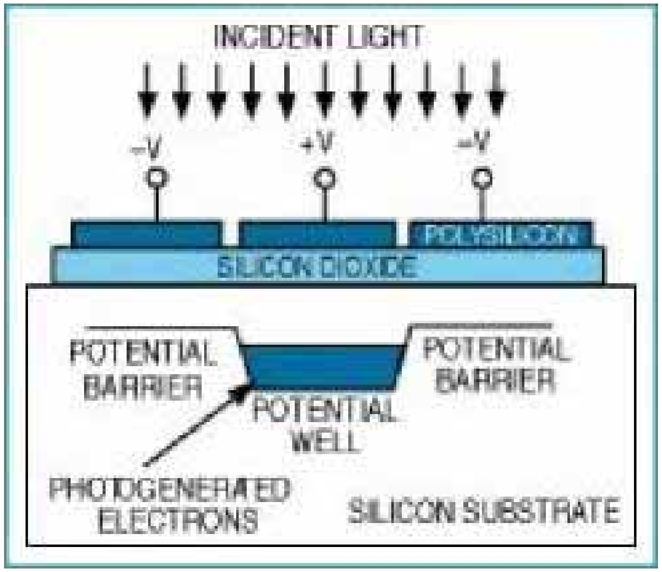


Charge Transfer Technique

w.wang

MOS capacitor

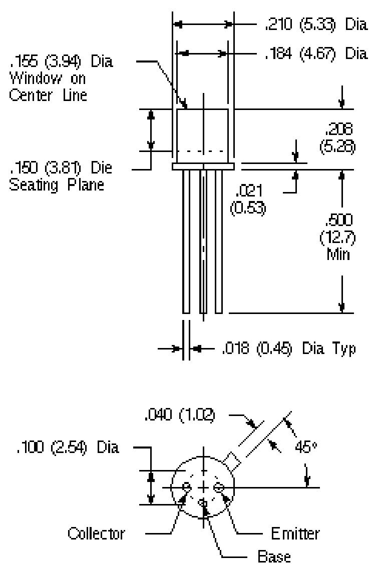
Charge is collected in potential well created by applying a voltage to the polysilicon, or gate electrode. The charge is confined in the well associated with each pixel by surrounding zones of higher potential barrier.

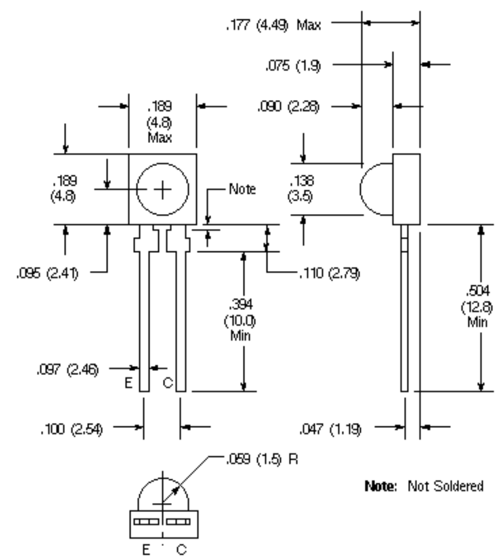


Mim Lal Nakarmi, KSU

Phototransistors

- Built in transistor amplifier





visay