# OPTICAL RECEIVERS

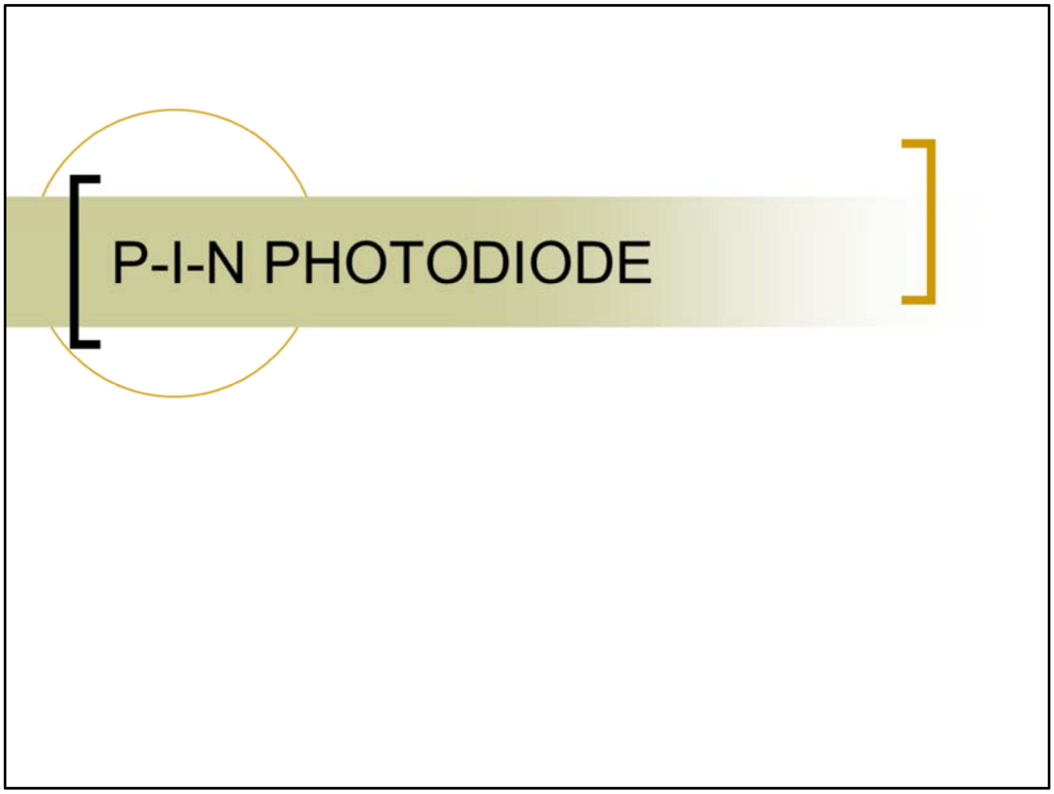
# P-I-N PHOTODIODE
# AVALANCHE PHOTODIODE

Silicon photodiodes are semiconductor devices responsive to high energy particles and photons.

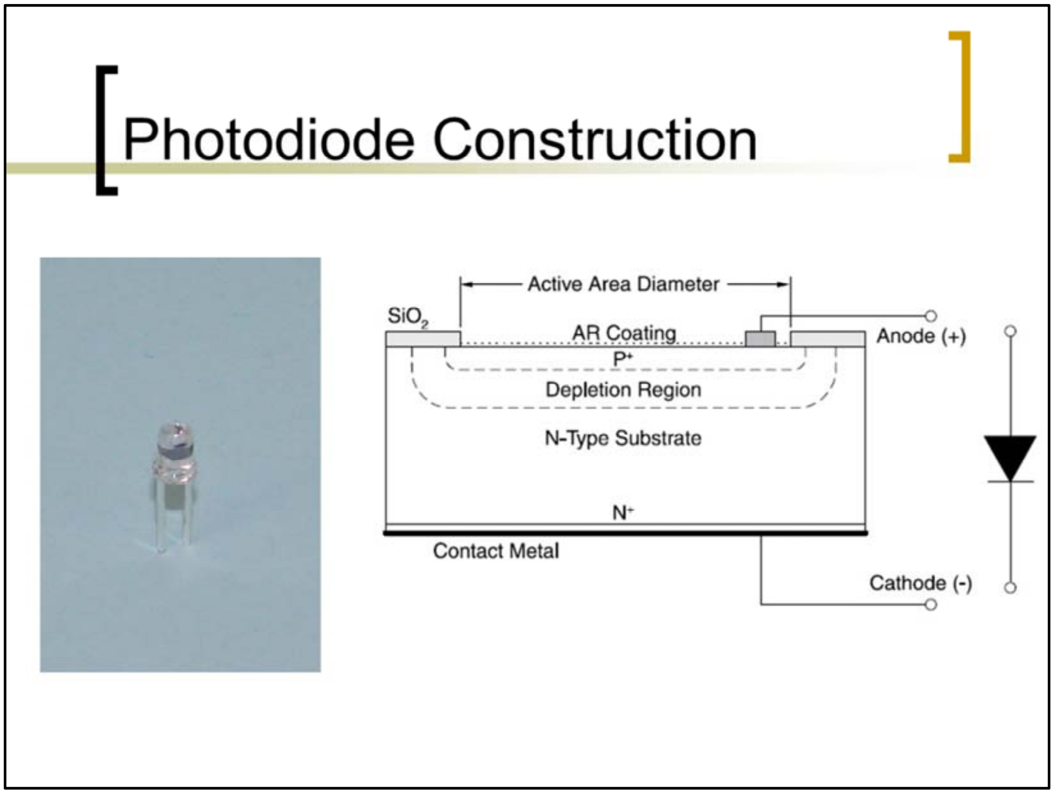
Photodiodes operate by absorption of photon and generate a flow of current in an external circuit, proportional to the incident power.

Photodiodes can be calibrated for extremely accurate measurements from intensities below 1 pW/cm2 to intensities above 100 mW/cm2.

Silicon photodiodes are utilized in such diverse applications as : spectroscopy, photography, analytical instrumentation, optical position sensors, beam alignment, surface characterization, laser range finders, optical communications, medical imaging instruments.



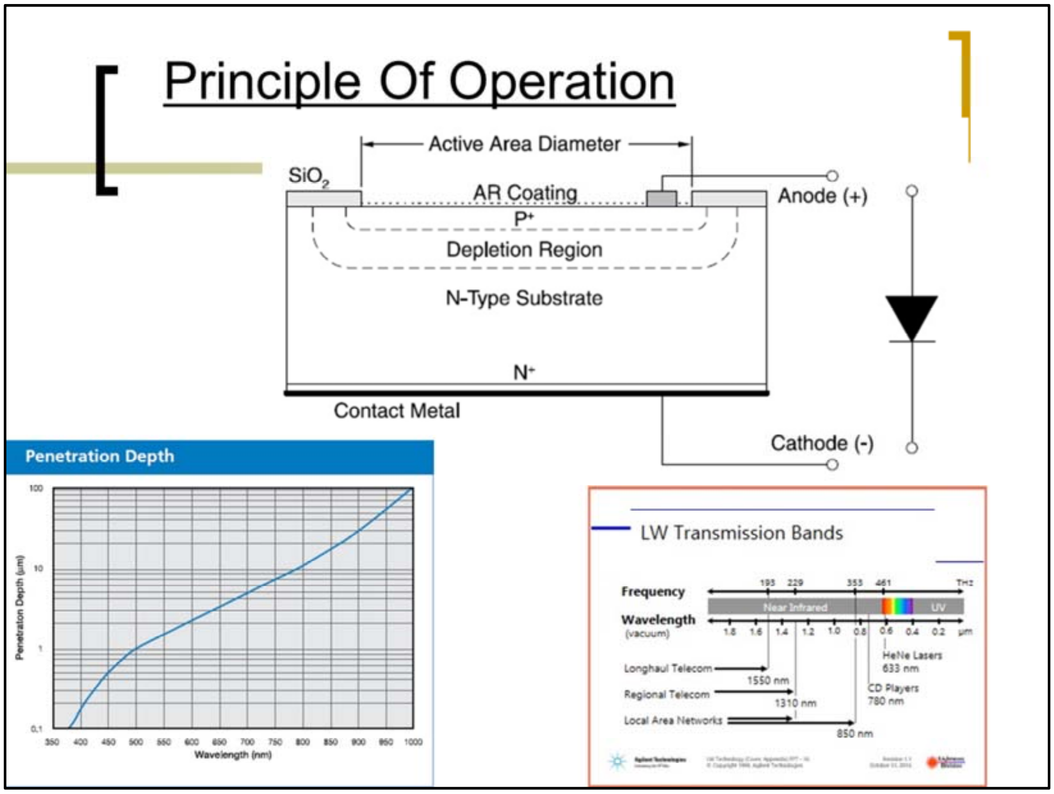

Fotodiode




Planar diffused silicon photodiodes are simply P-N junction diodes.

A P-N junction can be formed by diffusing either a P-type impurity (anode), such as Boron, into a N-type bulk silicon wafer, or a N-type impurity, such as Phosphorous, into a P-type bulk silicon wafer. The diffused area defines the photodiode active area. To form an ohmic contact another impurity diffusion into the backside of the wafer is necessary. The impurity is an N-type for P-type active area and P-type for an N-type active area. The contact pads are deposited on the front active area on defined areas, and on the backside, completely covering the device. The active area is then passivated with an anti-reflection coating to reduce the reflection of the light for a specific predefined wavelength. The non-active area on the top is covered with a thick layer of silicon oxide. By controlling the thickness of bulk substrate, the speed and responsivity of the photodiode can be controlled.

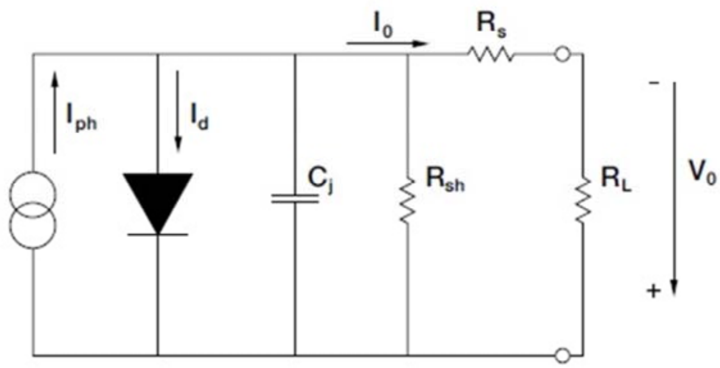
Note that the photodiodes, when biased, must be operated in the reverse bias mode, i.e. a negative voltage applied to anode and positive voltage to cathode.




Silicon is a semiconductor with a band gap energy of 1.12 eV at room temperature. This is the gap between the valence band and the conduction band. At absolute zero temperature the valence band is completely filled and the conduction band is vacant. As the temperature increases, the electrons become excited and escalate from the valence band to the conduction band by thermal energy. The electrons can also be escalated to the conduction band by particles or photons with energies greater than 1.12eV, which corresponds to wavelengths shorter than 1100 nm. The resulting electrons in the conduction band are free to conduct current.

Due to concentration gradient, the diffusion of electrons from the N-type region to the P-type region and the diffusion of holes from the P-type region to the N-type region, develops a built-in voltage across the junction. The inter-diffusion of electrons and holes between the N and P regions across the junction results in a region with no free carriers. This is the depletion region. The built-in voltage across the depletion region results in an electric field with maximum at the junction and no field outside of the depletion region. Any applied reverse bias adds to the built in voltage and results in a wider depletion region. The electron-hole pairs generated by light are swept away by drift in the depletion region and are collected by diffusion from the undepleted region. The current generated is proportional to the incident light or radiation power. The light is absorbed exponentially with distance and is proportional to the absorption coefficient. The absorption coefficient is very high for shorter wavelengths in the UV region and is small for longer wavelengths (Figure). Hence, short wavelength photons such as UV, are absorbed in a thin top surface layer while silicon becomes transparent to light wavelengths longer than 1200 nm. Moreover, photons with energies smaller than the band gap are not absorbed at all.

## Electrical Characteristics




$$R_S = \frac{(W_S - W_d)\rho}{A} + R_c \quad (1)$$

A silicon photodiode can be represented by a current source in parallel with an ideal diode (Figure). The current source represents the current generated by the incident radiation, and the diode represents the p-n junction. In addition, *a junction capacitance* (Cj) and *a shunt resistance* ($R_{SH}$) are in parallel with the other components. *Series resistance* (RS) is connected in series with all components in this model.

**Sunt Resistence, Rsh**

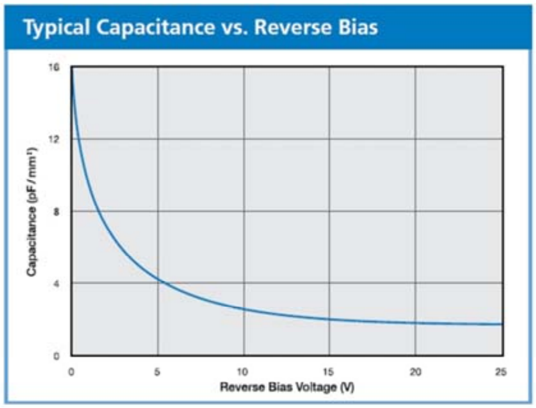
Shunt resistance is the slope of the current-voltage curve of thephotodiode at the origin, i.e. V=0. Although an ideal photodiode should have an infinite shunt resistance, actual values range from 10's to 1000's of Mega ohms. Experimentally it is obtained by applying ±10 mV, measuring the current and calculating the resistance. Shunt resistance is used to determine the noise current in the photodiode with no bias (photovoltaic mode). For best photodiode performance the highest shunt resistance is desired.

**Rezistenta serie , Rs**

Series resistance of a photodiode arises from the resistance of the contacts and the resistance of the undepleted silicon (Figure). It is given by eq.(1).

Where WS is the thickness of the substrate, Wd is the width of the depleted region, A is the diffused area of the junction, $\rho$ is the resistivity of the substrate and RC is the contact resistance. Series resistance is used to determine the linearity of the photodiode in photovoltaic mode (no bias, V=0). Although an ideal photodiode should have no series resistance, typical values ranging from 10 to 1000 Ω's are measured.

# Electrical Characteristics- 2




$$C_j = \frac{\varepsilon_{Si}\varepsilon_0 A}{\sqrt{2\varepsilon_{Si}\varepsilon_0 \mu\rho\left(V+V_{bi}\right)}} \quad (2)$$

$$= A\sqrt{\frac{\varepsilon_{Si}\varepsilon_0}{2\mu\rho\left(V+V_{bi}\right)}}$$

$$= \frac{\varepsilon_{Si}\varepsilon_0 A}{W_d}$$

$$W_d = \sqrt{2\varepsilon_{Si}\varepsilon_0 \mu\rho\left(V+V_{bi}\right)}$$

**Jonction Capacitance, Cj**

The boundaries of the depletion region act as the plates of a parallel plate capacitor (Figure). The junction capacitance is directly proportional to the diffused area and inversely proportional to the width of the depletion region, Wd. In addition, higher resistivity substrates have lower junction capacitance. Furthermore, the capacitance is dependent on the reverse bias as in Eq.(2), where ε0 = 8.854x10-14 F/cm, is the permittivity of free space, ε(Si) =11.9 is the silicon dielectric constant, µ = 1400 cm2/Vs is the mobility of the electrons at 300 K, ρ is the resistivity of the silicon, Vbi is the builtin voltage of silicon and VA is the applied bias. Figure shows the dependence of the capacitance on the applied reverse bias voltage. Junction capacitance is used to determine the speed of the response of the photodiode.

## Electrical Characteristics - 3

$$t_r = \frac{0.35}{f_{3dB}} \quad (3)$$

$$t_{RC} = 2.2RC \quad (4)$$

$$t_R = \sqrt{t_{DRIFT}^2 + t_{DIFFUSION}^2 + t_{RC}^2} \quad (5)$$

**Rise / Fall Time and Frequency Response, tr / tf / f3dB**

The rise time and fall time of a photodiode is defined as the time for the signal to rise or fall from 10% to 90% or 90% to 10% of the final value respectively. This parameter can be also expressed as frequency response, which is the frequency at which the photodiode output decreases by 3dB. It is roughly approximated by Eq.( 3 )

There are three factors defining the response time of a photodiode:

1. tDRIFT, the charge collection time of the carriers in the depleted region of the photodiode.

2. tDIFFUSED, the charge collection time of the carriers in the undepleted region of the photodiode.

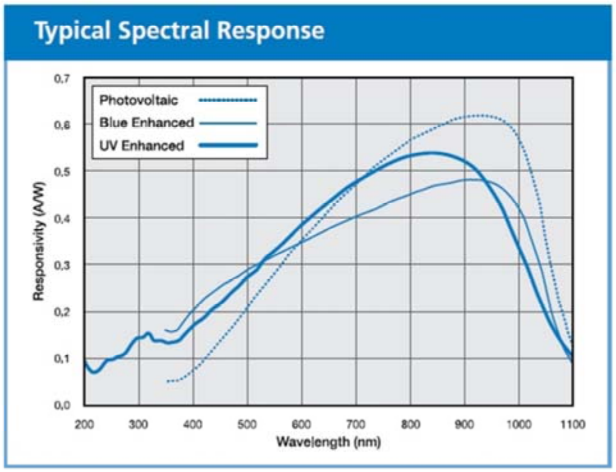
3. tRC, the RC time constant of the diode-circuit combination.

tRC is determined by Eq.(4), where R, is the sum of the diode series resistance and the load resistance (RS + RL), and C, is the sum of the photodiode junction and the stray capacitances (Cj+CS). Since the junction capacitance (Cj) is dependent on the diffused area of the photodiode and the applied reverse bias (Equation 2), faster rise times

are obtained with smaller diffused area photodiodes, and larger applied reverse biases. In addition, stray capacitance can be minimized by using short leads, and careful lay-out of the electronic components. The total rise time is determined by Eq.( 4 )

Generally, in photovoltaic mode of operation (no bias), rise time is dominated by the diffusion time for diffused areas less than 5 mm2 and by RC time constant for larger diffused areas for all wavelengths. When operated in photoconductive mode (applied reverse bias), if the photodiode is fully depleted, such as high speed series, the dominant factor is the drift time. In non-fully depleted photodiodes, however, all three factors contribute to the response time.

## Optical Characteristics

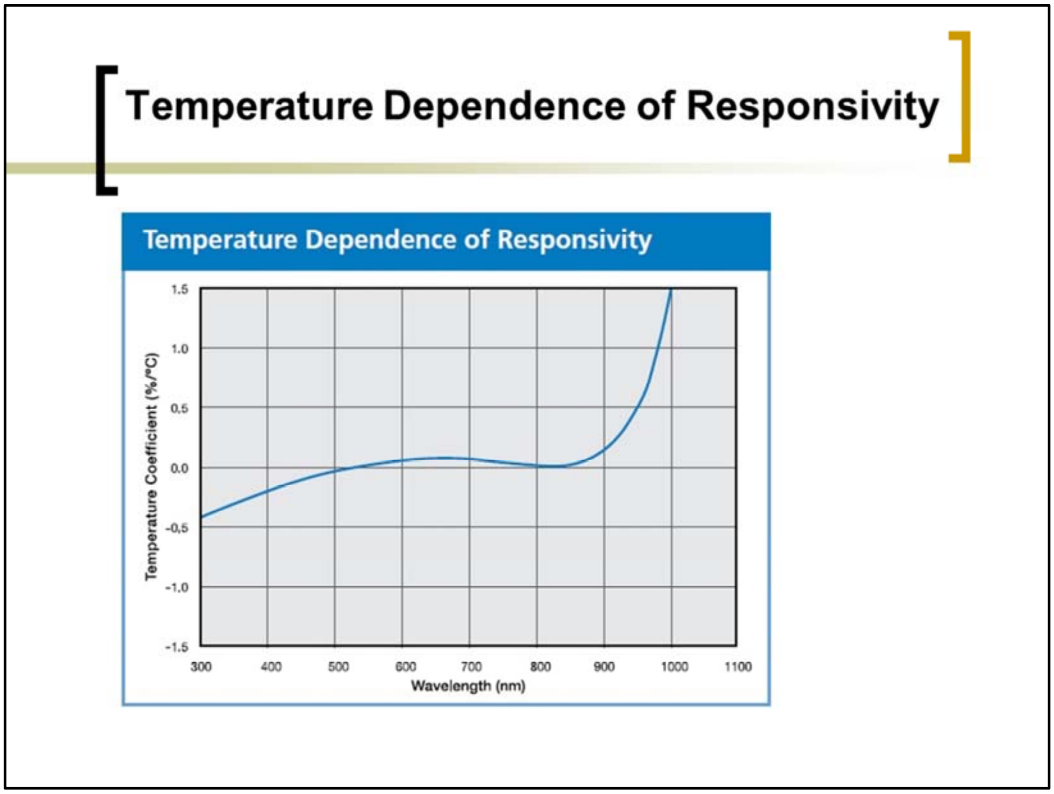



$$R_\lambda = \frac{I_P}{P} \quad (6)$$

**<u>Responsivity, R(λ)</u>**

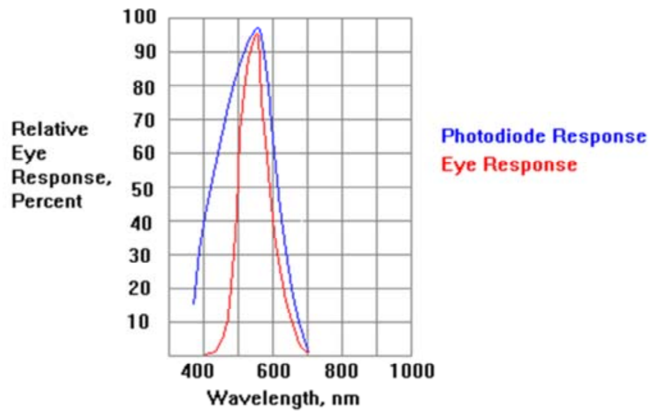
The responsivity of a silicon photodiode is a measure of the sensitivity to light, and it is defined as the ratio of the photocurrent IP to the incident light power P at a given wavelength, Eq.(6). It varies with the wavelength of the incident light (Figure) as well as applied reverse bias and temperature.

Responsivity increases slightly with applied reverse bias due to improved charge collection efficiency in the photodiode.




There are responsivity variations due to change in temperature as shown in figure. This is due to decrease or increase of the band gap, because of increase or decrease in the temperature respectively.

# Spectral responsivity



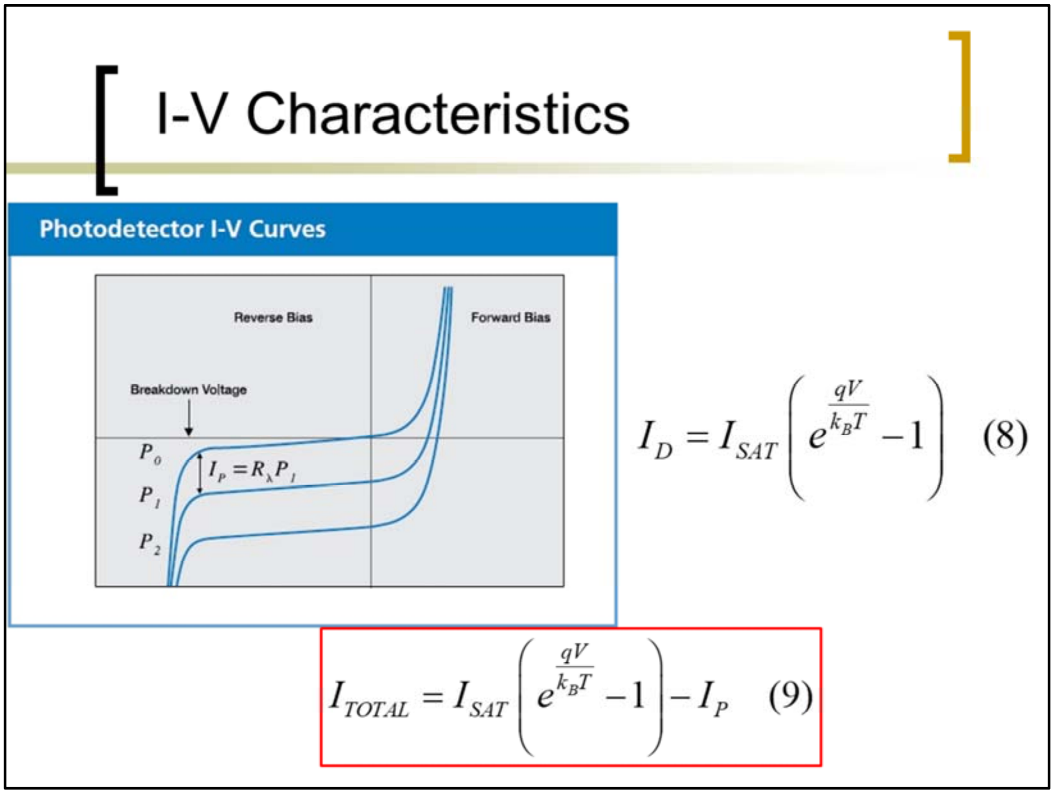

Spectral responsivity may vary from lot to lot and it is dependent on wavelength. However, the relative variations in responsivity can be reduced to less than 1% on a selected basis.

# Quantum Efficiency . Q.E.

$$Q.E. = \frac{R_{\lambda,real}}{R_{\lambda,ideal}} = R_{\lambda}\frac{hc}{\lambda q} = 1240\frac{R_{\lambda}}{\lambda} \quad (7)$$

**Quantum Efficiency, Q.E.**

Quantum efficiency is defined as the fraction of the incident photons that contribute to photocurrent. It is related to responsivity by Eq.(7), where h=6.63 x 10-34 J*s, is the Planck constant, c=3 x 108 m/s, is the speed of light, q=1.6 x 10-19 C, is the electron charge, $R\lambda$ is the responsivity in A/W and $\lambda$ is the wavelength in nm.




**I-V Characteristics**

The current-voltage characteristic of a photodiode with no incident light is similar to a rectifying diode. When the photodiode is forward biased, there is an exponential increase in the current. When a reverse bias is applied, a small reverse saturation current appears. It is related to dark current as Eq.(8), where ID is the photodiode dark current, ISAT is the reverse saturation current, q is the electron charge, VA is the applied bias voltage, kB=1.38 x 10-23 J / K, is the Boltzmann Constant and T is the absolute temperature (273 K= 0 ºC).

This relationship is shown in figure. From equation 8, three various states can be defined:

a) V = 0, In this state, the dark current IP=0.

b) V = +V, In this state the current increases exponentially. This state is also known as forward bias mode.

c) V = -V, When a very large reverse bias is applied to the photodiode, the dark current becomes the reverse saturation current, ISat.

Illuminating the photodiode with optical radiation, shifts the I-V curve by the amount of photocurrent (IP). Thus we have Eq.(9), where IP is defined as the photocurrent in equation 6 from slide 9.

As the applied reverse bias increases, there is a sharp increase in thephotodiode current. The applied reverse bias at this point is referred to as breakdown voltage. This is the maximum applied reverse bias, below which, the photodiode should be operated (also known as maximum reverse voltage). Breakdown voltage, varies from one photodiode to another and is usually measured, for small active areas, at a dark current of 10 µA.

## Noise

- Shot Noise
- Thermal or Johnson Noise

In a photodiode, two sources of noise can be identified; Shot noise and Johnson noise.

## Noise

- Shot Noise

$$I_{sn} = \sqrt{2q\left(I_P + I_D\right)\left(\Delta f\right)_{PD}} \quad (10)$$

**Shot Noise**

Shot noise is related to the statistical fluctuation in both the photocurrent and the dark current. The magnitude of the shot noise is expressed as the root mean square (rms) noise current, Eq.(10). where q=1.6x10-19C, is the electron charge, IP is the photogenerated current, ID is the photodetector dark current and Δf is the noise measurement bandwidth. Shot noise is the dominating source when operating in photoconductive (biased) mode.

## Noise

- Thermal or Johnson Noise

$$I_{jn} = \sqrt{\frac{4k_B T (\Delta f)_{PD}}{R_{SH}}} \quad (11)$$

**Thermal or Johnson Noise**

The shunt resistance in a photodetector has a Johnson noise associated with it. This is due to the thermal generation of carriers. The magnitude

of this generated noise current is Eq.(11), where kB=1.38 x 10-23 J/K, is the Boltzmann Constant, T, is the absolute temperature in degrees Kelvin (273 K= 0 ºC), Δf is the

noise measurement bandwidth and $R_{SH}$ , is the shunt resistance of the photodiode. This type of noise is the dominant current noise in photovoltaic (unbiased) operation mode.

## Noise

- Total Noise

$$I_{tn} = \sqrt{I_{sn}^2 + I_{jn}^2} \quad (12)$$

**Total Noise**

The total noise current generated in a photodetector is determined by Eq.(12)

## Noise

- Noise Equivalent Power (NEP)

$$NEP = \frac{I_{tN}}{R_\lambda} = \frac{I_{tn} / \sqrt{\Delta f}}{R_\lambda} \qquad (13)$$

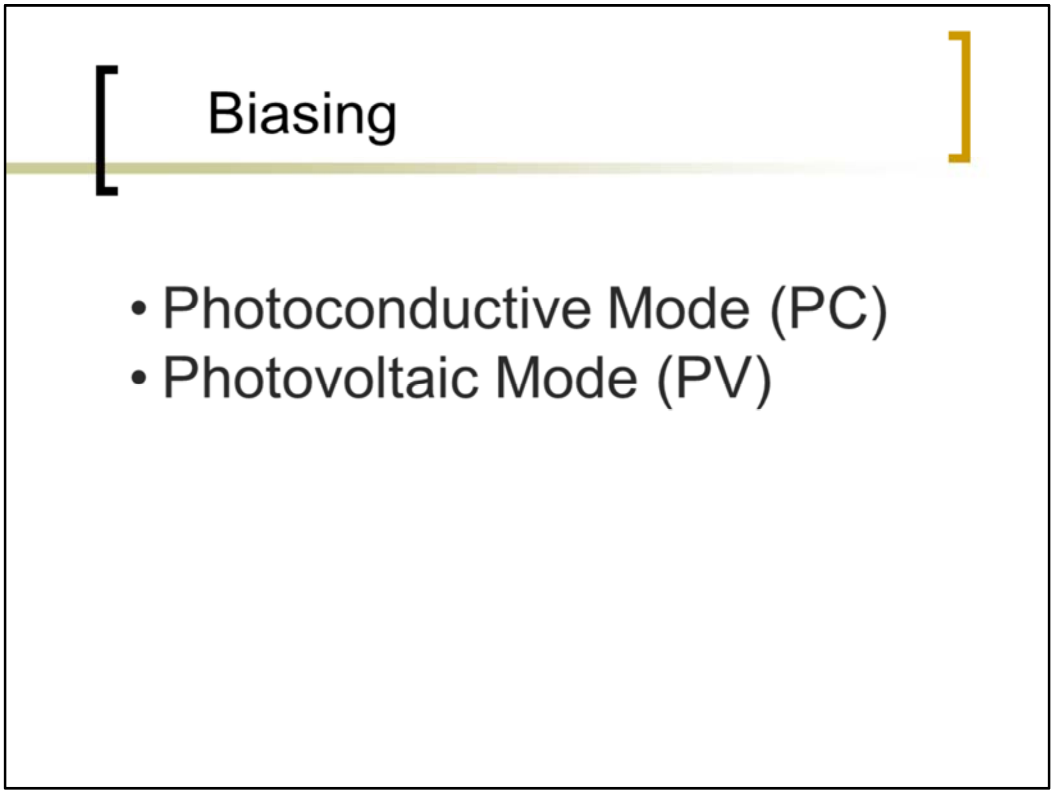
**<u>Noise Equivalent Power (NEP)</u>**

Noise Equivalent Power is the amount of incident light power on a photodetector, which generates a photocurrent equal to the noise current. NEP is defined in Eq.(13), where Rλ is the responsivity in A/W and Itn is the total noise of the photodetector. NEP values can vary from 10-11 W/√Hz for large active area photodiodes down to 10-15 W /√Hz for small active area photodiodes.

All photodiode characteristics are affected by changes in temperature. They include shunt resistance, dark current, breakdown voltage, responsivity and to a lesser extent other parameters such as junction capacitance.

## ELECTRO-OPTICAL CHARACTERISTICS RATING (TA)= 23°C UNLESS OTHERWISE NOTED

| SYMBOL | CHARACTERISTIC | TEST CONDITIONS | MIN | TYP | MAX | UNITS |
|---|---|---|---|---|---|---|
| $I_{SC}$ | Short Circuit Current | H = 100 fc, 2850 K | 50 | 60 | | $\mu$A |
| $I_D$ | Dark Current | $V_R$ = 10 V | | 2 | 30 | nA |
| $R_{SH}$ | Shunt Resistance | $V_R$ = 10 mV | 0.5 | 2 | | G$\Omega$ |
| $C_J$ | Junction Capacitance | $V_R$ = 10 V, $f$ = 1 MHz | | 6 | 10 | pF |
| $\lambda$range | Spectral Application Range | Spot Scan | 400 | | 1100 | nm |
| $V_{BR}$ | Breakdown Voltage | I = 10 $\mu$A | 50 | 100 | | V |
| NEP | Noise Equivalent Power | $V_R$ = 10V @ $\lambda$ = Peak | | $1.8 \times 10^{-13}$ | | W/ $\sqrt{Hz}$ |
| $t_r$ | Response Time | RL = 1K$\Omega$, $V_R$ = 50 V | | 10 | | nS |

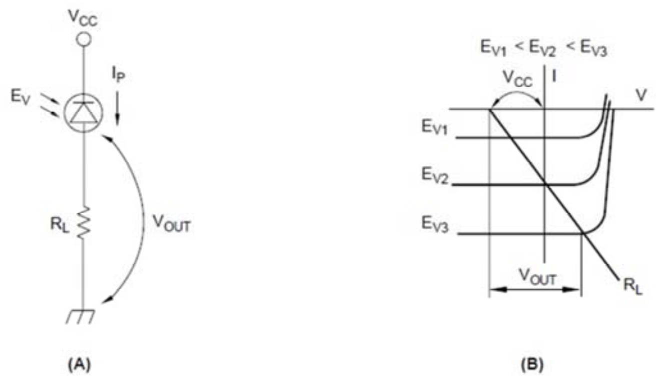



**Biasing**

A photodiode signal can be measured as a voltage or a current. Current measurement demonstrates far better linearity, offset, and bandwidth performance. The generated photocurrent is proportional to the incident light power and it must be converted to voltage using a transimpedance configuration. The photodiode can be operated with or

without an applied reverse bias depending on the application specific requirements. They are referred to as “Photoconductive” (biased) and “Photovoltaic” (unbiased) modes.

# Biasing - PC




$$V_{OUT} = I_P \times R_L$$

**Photoconductiv Mode – PC (with bias)**

Figure shows a circuit in which the photodiode is reverse-biased by VCC and a photocurrent (IP) is transformed into an output voltage. Also in this arrangement, the VOUT is given as VOUT = IP × RL. An output voltage proportional to the amount of incident light is obtained. The proportional region is expanded by the amount of VCC (proportional region: VOUT < (VOC + VCC)}. On the other hand, application of reverse bias to the photodiode causes the dark current (Id) to increase, leaving a voltage of Id × RL when the light is interrupted, and this point should be noted in designing the circuit. Figure 2 (B) shows the operating point for a load resistor RL with reverse bias applied to the photodiode.

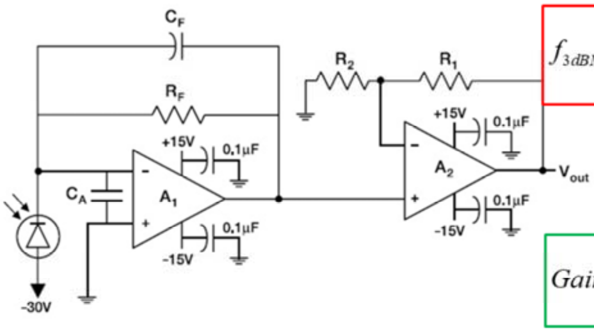
Features of a circuit used with a reverse-biased photodiode are:

• High-speed response

• Wide-proportional-range of output

Therefore, this circuit is generally used.

## Biasing - PC




$$f_{3dBMax}\left[Hz\right] = \sqrt{\frac{GBP}{2\pi R_F \left(C_j + C_F + C_A\right)}} \quad (14)$$

$$Gain\left[V/W\right] = \frac{V_{OUT}}{P} = R_F\left(1 + \frac{R_1}{R_2}\right)R_\lambda \quad (15)$$

| | |
|---|---|
| Amplifier : | OPA-637, OPA-846, OPA-847, or similar |
| $R_F$: | 1 to 10 KΩ Typical, depending on $C_j$ |
| $R_1$: | 10 to 50 kΩ |
| $R_2$: | 0.5 to 10 kΩ |
| $C_F$: | 0.2 to 2 pF |

**Photoconductiv Mode – PC (with bias)**

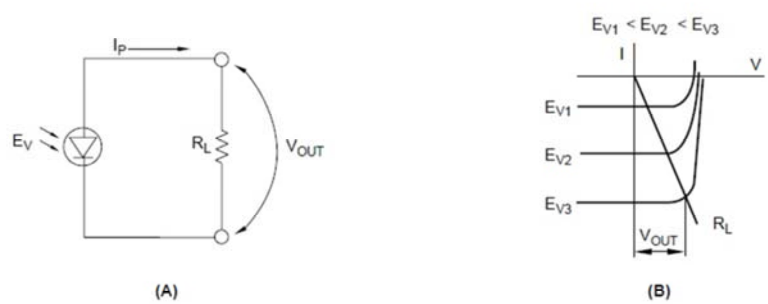
Application of a reverse bias (i.e. cathode positive, anode negative) can greatly improve the speed of response and linearity of the devices. This is due to increase in the depletion region width and consequently decrease in junction capacitance. Applying a reverse bias, however, will increase the dark and noise currents. An example of low light level / high-speed response operated in photoconductive mode is shown in figure.

In this configuration the detector is biased to reduce junction capacitance thus reducing noise and rise time (tr). A two stage amplification is used in this example since a high gain with a wide bandwidth is required. The two stages include a transimpedance pre-amp for current- to-voltage conversion and a non-inverting amplifier for voltage amplification. Gain and bandwidth (f3dB Max) are directly determined by RF, per equations (14) and (15) . The gain of the second stage is approximated by 1+ R1 / R2.

A feedback capacitor (CF) will limit the frequency response and avoids gain peaking. GBP is the Gain Bandwidth Product of amplifier (A1) and CA is the amplifier input capacitance.

Typical components used in this configuration are in the table.

# Biasing - PV




$$V_{OUT} = I_P \times R_L$$

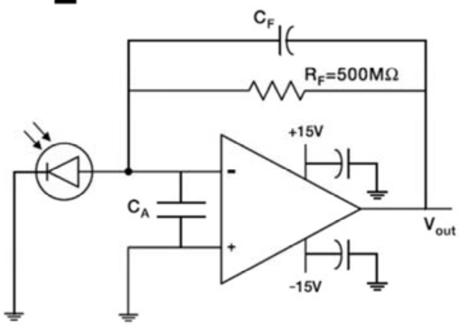
**Photovoltaic Mode – PV (without bias)**

The circuit shown in Figure (A) transforms a photocurrent produced by a photodiode without bias into a voltage. The output voltage (VOUT) is given as

VOUT = IP × RL. It is more or less proportional to the amount of incident light when VOUT < VOC. It can also be compressed logarithmically relative to the amount of incident light when VOUT is near VOC. (VOC is the open-terminal voltage of a photodiode).

Figure(B) shows the operating point for a load resistor (RL) without application of bias to the photodiode.

## Biasing - PV




$$f_{OP}[Hz] = \frac{1}{2\pi R_F C_F} \quad (16)$$

$$V_{OUT} = R_F \times I_P \quad (17)$$

$$I_N\left[\frac{A}{\sqrt{Hz}}\right] = \sqrt{\frac{4k_B T}{R_F}} \quad (18)$$

| | |
|---|---|
| Amplifier : | OPA111, OPA124, OPA627 or similar |
| $R_F$ : | 500 MΩ |

$$\sqrt{\frac{GBP}{2\pi R_F\left(C_j + C_F + C_A\right)}} > \frac{1}{2\pi R_F C_F} \quad (19)$$

**Photovoltaic Mode – PV (without bias)**

The photovoltaic mode of operation (unbiased) is preferred when a photodiode is used in low frequency applications (up to 350 kHz) as well as ultra low light level applications. In addition to offering a simple operational configuration, the photocurrents in this mode have less variations in responsivity with temperature. An example of an ultra low light level / low speed is shown in figure.

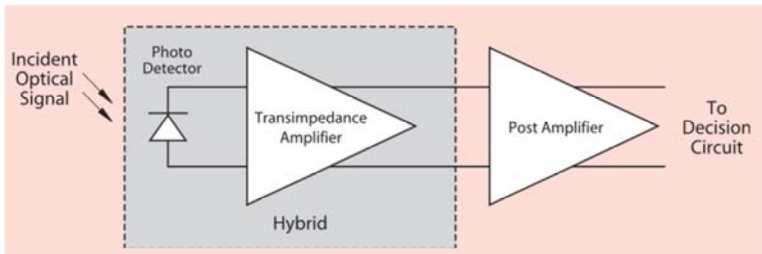
In this example, a FET input operational amplifier as well as a large resistance feedback resistor (RF) is considered. The detector is unbiased to eliminate any additional noise current. The total output is determined by equation (17) and the op-amp noise current is determined by RF in equation (18), where k=1.38 x 10-23 J/K and T is temperature in K.

For stability, select CF such as indicated in Eq.(16).

Operating bandwidth, after gain peaking compensation is given by Eq.(19).

Some recommended components for this configuration are in the table.

# Receiver design of optical signal




As it is shown on Figure , optical receiver in digital communication system typically contains of Photo Detector, Transimpedance Amplifier (TIA), and Post Amplifier then followed by decision circuit. Photo Detector (PD), typically PIN or Avalanche Photo Diode (APD), produces photocurrent proportional to the incident optical power. Transimpedance amplifier converts this current into voltage signal and then Post Amplifier bring this voltage to some standard level, so Post Amplifier output signal can be used by decision circuit.

## Receiver design of optical signal - 2


$$P_{AVG} = \frac{P_0 + P_1}{2} \quad (20)$$

$$P_{P-P} = P_1 - P_0 \quad (21)$$

In digital optical communication system binary data stream is transmitted by modulation of optical signal. Optical signal with non-return-to-zero (NRZ) coding may have one of two possible state of optical power level during bit time interval. Higher optical power level corresponds to logic level 1, lower level corresponds to 0. In the real system optical power does not equal to zero when transmitting logical 0. Let's assume, that 0 state power equal to P0 and 1 - state power equal to P1 as it is indicated
on Figure.
The system can be described in terms of Average Power PAVG and Optical Modulation Amplitude or Peak-to-Peak Optical Power PP-P. It is very important to note that we will consider below systems with probabilities to have "one" or "zero" at the output equal to each other (50%). So we can easily determine the equations (20) and (21)

# Receiver design of optical signal-3


$$r_e = \frac{P_1}{P_0} \quad (22)$$

$$r_e(dB) = 10\,log\left(\frac{P_1}{P_0}\right)$$

$$P_{AVG} = \frac{1}{2}\frac{(r_e+1)}{(r_e-1)}P_{P-P} \quad (23)$$

Extinction Ratio re is the ratio between P1 and P0, eq.(22).
Extinction ratio can be expressed in terms of dB.
Then, the average power in terms of peak-to-peak power and extinction ratio is in eq. (23)

# EXAMPLE

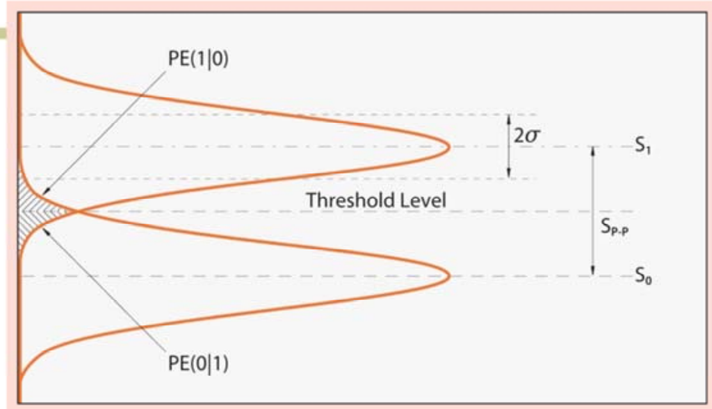
$$P_{AVG} = -17\,dBm$$
$$r_e = 9\,dB$$

$$P_{AVG} = 20\,\mu W$$
$$r_e = 7.94$$

$$P(mW) = 10^{(P(dBm)/10)}$$

$$P_{P-P} = 2\frac{(r_e - 1)}{(r_e + 1)}P_{AVG}$$
$$= 2\frac{(7.94-1)}{(7.94+1)} \times 20\,\mu W = 1.55 \times 20\,\mu W = 31\,\mu W_{P-P} \qquad (24)$$

## Sensitivity and BER




$$PE = \frac{1}{2}\left[PE\left(0|1\right) + PE\left(1|0\right)\right] \quad (25)$$

$$D_P\left(X\right) = \frac{1}{\sigma\sqrt{2\pi}} exp\left(-\frac{\left(X-\mu\right)^2}{2\sigma^2}\right) \quad (26)$$

Number of errors at the output of decision circuit will determine the quality of the receiver and of course the quality of transmission system.
Bit-error-rate (BER) is the ratio of detected bit errors to number of total bit transmitted. Sensitivity S of the optical receiver is determined as a minimum optical power of the incident light signal that is necessary to keep required Bit Error Rate. Sensitivity can be expressed in terms of Average Power (dBm, sometimes µW) with given Extinction
Ratio (dB) or in terms of Peak-to-Peak Optical Power (µWP-P). BER requirements are specified for different applications, for example some telecommunication applications specify BER to be 10-10 or better; for some data communications it should be equal or better than $10^{-12}$.
Noise is one of the most important factors of errors. Noise of PIN Photodiode in digital high-speed application system is typically much less than noise of transimpedance amplifier. Considering thermal noise of TIA as an only noise in such a system usually gives good result for PD/ TIA hybrid analysis. We can estimate error probability PE when assuming Gaussian distribution for thermal noise of amplifier, eq.(25), where PE(0|1) and PE(1|0) probability to decide 0 instead of 1; and 1 instead of 0 correspondingly when we have equal probabilities for 0 and 1 in our system.

Probability density function Dp for Gaussian distribution is eq.(26), where χ – distribution parameter, σ – is standard deviation, and µ – is mean value. Probability density functions are shown on Figure for two levels of signal.

# Sensitivity and BER - 2


$$PE\left(1|0\right) = \int_{Prag}^{\infty} D_{P_0}\left(X\right) dX \quad (27)$$

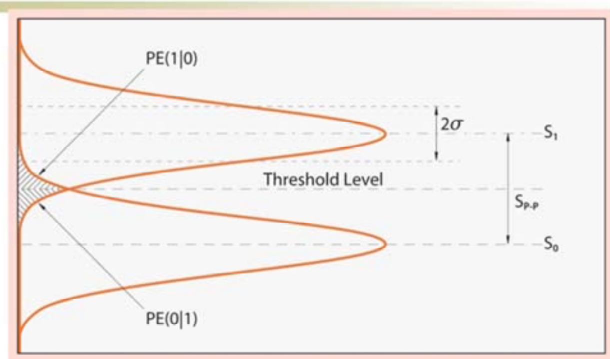
$$PE\left(1|0\right) = \int_{S_{P-P}/2}^{\infty} \frac{1}{\sigma\sqrt{2\pi}} exp\left(-\frac{\left(X\right)^2}{2\sigma^2}\right) dX \quad (28)$$

$$t = \frac{X}{\sigma} \quad (29)$$

$$PE\left(1|0\right) = \int_{S_{P-P}/2\sigma}^{\infty} \frac{1}{\sqrt{2\pi}} exp\left(-\frac{t^2}{2}\right) dt \quad (30)$$

To estimate probability of incorrect decision, for example PE(1|0), we need to integrate density function for 0-distribution above threshold level.
Considering symmetrical distributions (threshold is the half of peak-to-peak signal $S_{P-P}$), we optain eq.(28).
Then normalizing to eq.(29) we obtain eq.(30).

# Sensitivity and BER - 3




$$PE = erfc\left(\frac{SNR}{2}\right) \quad (31)$$

$$erfc(x) \stackrel{d}{=} \int_{x}^{\infty} \frac{1}{\sqrt{2\pi}} exp\left(-\frac{t^2}{2}\right) dt \quad (32)$$

If deviations for 0 and 1 levels are equal, total probability of error will be given by eq.(31), where erfc(x) is the complimentary error function, given in (32), and SNR – signal-to-noise ratio, where signal is in terms of peak-to-peak and noise is an RMS value.

# Sensitivity and BER - 4


| *BER* | $10^{-08}$ | $10^{-09}$ | $10^{-10}$ | $10^{-11}$ | $10^{-12}$ |
|---|---|---|---|---|---|
| *SNR* | 11.22 | 11.99 | 12.72 | 13.40 | 14.06 |

Graph of erfc(x) is shown on Figure and some tabulated SNR numbers vs. BER are given

# Sensitivity and BER - 5

$$SNR = \frac{I_{P-P}}{I_{N,ef}} = \frac{P_{P-P} \times R_{\lambda}}{I_{N,ef}} \quad (33)$$

$$P_{P-P} = \frac{SNR \times I_{N,ef}}{R_{\lambda}} \quad (34)$$

$$S = P_{AVG@BER} = \frac{SNR \times I_{N,ef}}{2R_{\lambda}} \frac{r_e + 1}{r_e - 1} \quad (35)$$

| $r_e$, dB | 7.00 | 8.00 | 9.00 | 10.00 | $\infty$ |
|---|---|---|---|---|---|
| $r_e$ | 5.01 | 6.31 | 7.94 | 10.00 | $\infty$ |
| Power Penalty, dB | 1.76 | 1.39 | 1.10 | 0.87 | 0 |

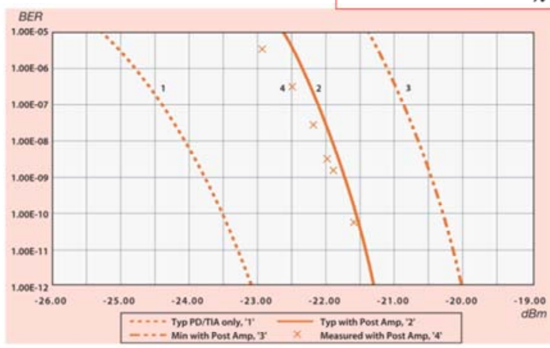
We can find peak-to-peak signal that we need to achieve required BER, eq.(33), where I_P-P is signal photocurrent, R – photodetector responsivity expressed in A/W, I_N,RMS – input equivalent RMS noise of TIA, eq.(34).
To estimate the sensitivity of PD/TIA at certain BER, we need to find required SNR in the Table from slide 31, and then calculate average power using equation (35), where the first term is the sensitivity with an infinite extinction ratio, and the second is the correction for finite extinction ratio or extinction ratio penalty.
Some numbers for extinction ratio penalty are shown in the Table.

# Sensitivity and BER - 6

$$\Delta I_{PA} = \frac{V_{TH}}{R_{TIA}} \quad (36)$$

$$P_{P-P} = \frac{SNR \times I_{N,ef} + \Delta I_{PA}}{R_\lambda} \quad (37)$$

$$S = \frac{SNR \times I_{N,ef} + \frac{V_{TH}}{R_{TIA}}}{2R_\lambda} \times \frac{r_e + 1}{r_e - 1} \quad (38)$$




To calculate total receiver sensitivity we have to consider also sensitivity of Post Amplifier or Input Threshold Voltage VTH. Sensitivity of Post Amplifier should be indicated in the Post Amplifier Datasheet and it is usually expressed in peak-to peak Volts value (mVP-P). To achieve the same BER we need to increase peak-to-peak current at least by value given in eq.(36), where RTIA is transimpedance coefficient of TIA.

Peak-to-peak optical power will be given by eq.(37) and sensitivity by eq.(38).

Figure presents InGaAs PD/TIA hybrid: sensitivity for PD/TIA only (curve 1), calculated for PD/TIA with 10mV threshold Post Amplifier typical (curve 2) and minimum (curve 3),

and actual measurements for PD/TIA-Post Amplifier system (X-points 4).

# EXAMPLE

Let's calculate the sensitivity for 2.5Gbps InGaAs PD/TIA hybrid at BER=$10^{-10}$, assuming responsivity of detector to be 0.9 A/W, input RMS noise current of the transimpedance amplifier 500nA, and the extinction ratio of the optical signal 9dB.

$$BER = 10^{-10} \qquad SNR = 12.72$$

$$r_e = 9dB = 7.94$$

$$S = \frac{12.72 \times 0.5\mu A(7.94+1)}{2 \times 0.9\, A/W(7.94-1)} = 4.56\mu W = -23.4dBm$$

$$V_{TH} = 10mV \qquad R_{TIA} = 2{,}8k\Omega$$

$$S = \frac{12.72 \times 0.5\mu A(7.94+1) + \frac{10mV}{2.8k\Omega}}{2 \times 0.9\, A/W(7.94-1)} = 7.11\mu W = -21.5dBm$$

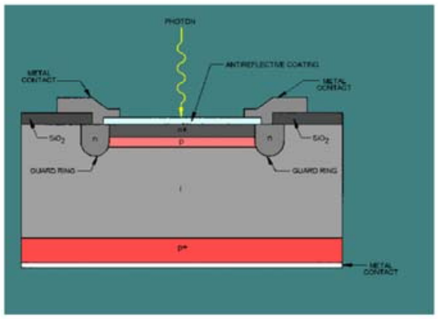
First, we will find SNR required to achieve BER=10-10 from the Table 1. Therefore, SNR = 12.72. Then, we can calculate the sensitivity considering re = 7.94, or S = -23.4 dBm

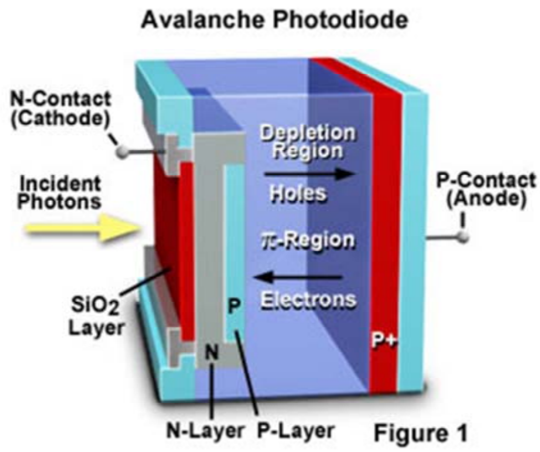
For combination of such a PD/TIA Hybrid and Post Amplifier with VTH = 10 mV assuming RTIA = 2.8k⍰ sensitivity will be…or S = -21.5 dBm.

This Post Amplifier threshold affects the sensitivity and the difference is 1.9 dB. Therefore it is very important to take performance and parameters of all discrete receiver components into consideration to analyze the sensitivity of the entire receiver system.

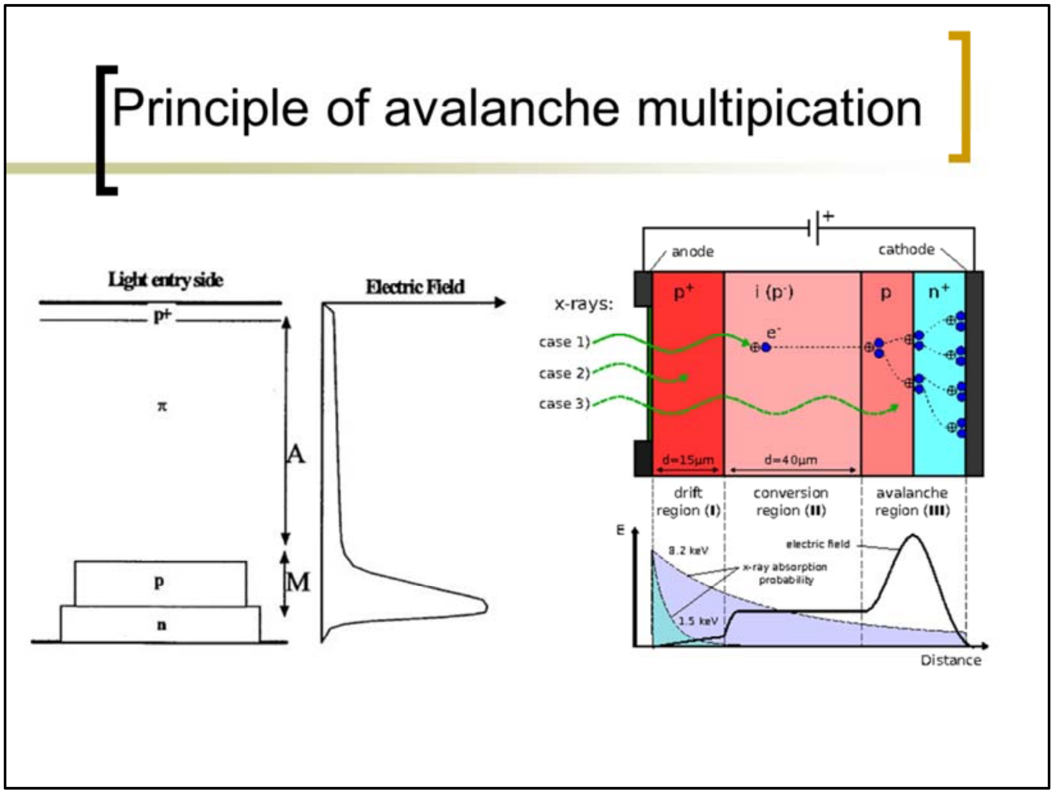
# AVALANCHE PHOTODIODE

# Avalanche Photodiode structure






The ideal APD would have zero dark noise, no excess noise, broad spectral and frequency response, a gain range from 1 to 106 or more, and low cost. More simply, an ideal APD would be a good PIN photodiode with gain! In




Consider the schematic cross-section for a typical APD structure shown in Figure. The basic structural elements provided by the APD designer include an absorption region "A", and a multiplication region "M". Present across region "A" is an electric field "E" that serves to separate the photo-generated holes and electrons, and sweeps one carrier towards the multiplication region. The multiplication region "M" is designed to exhibit a high electric field so as to provide internal photo-current gain by impact ionization.

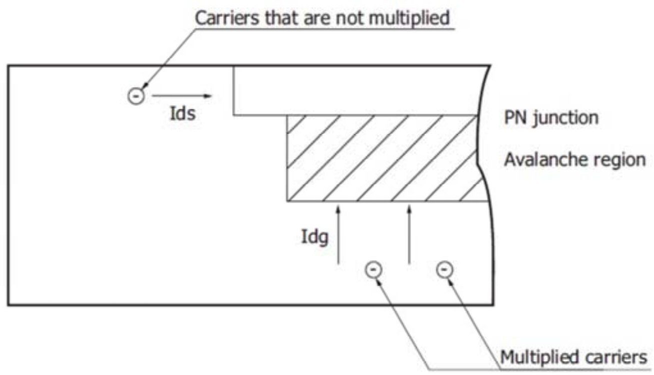
**Principle of avalanche multiplication**

The mechanism of photocurrent generation in APD is the same as in a normal photodiode: when light enters the photodiode, electron-hole pairs are generated if the light energy is greater than the energy of the band gap band. The ratio between the number of electron-hole pairs and the number of incident photons is defined as the quantum efficiency (QE), commonly expressed in as percent (%). But APD is different from a photodiode in that it also has a function to multiply the gnerated carriers.

When the electron-hole pairs are generated in the depletion layer of an APD with a reverse voltage applied applied to the PN junction, the electric field created along the PN junction causes the electrons to drift towards the N + region, and the holes to drift towards the P + region. The higher the electric field, the higher the drift speed of the carriers. However, when the electric field reaches a certain level, the carriers are more likely to collide with the cristal lattice and thus the drift speed becomes saturated at a certain value. If the electric field is increased even futher, carriers that escaped the collision with the crystal lattice will have a great deal of energy. When these carriers collide with the crystal lattice, a phenomenon takes place in which new electron-hole pairs are generated. This phenomenon is called ionization. These pairs generate a chain reaction of ionization. This is the phenomenon called avalanche multiplication.

The number of electron-hole pairs generated during the time that a carrier moves a unit distance is referred to as the ionization rate. Usually, the ionization rate of electrons is denoted by "α" and that of holes as "β". These ionization rates are important factors in determining the multiplication mechanism. In the case of silicon, the ionization rate of the electrons is larger than that of the holes (α> β), so the ratio at which the electrons contribute to multiplication increases. Thus, electrons will have to be favored to enter the avalanche region. The depth at which carriers are generated depends on the wavelength of the incident light.

## Dark current



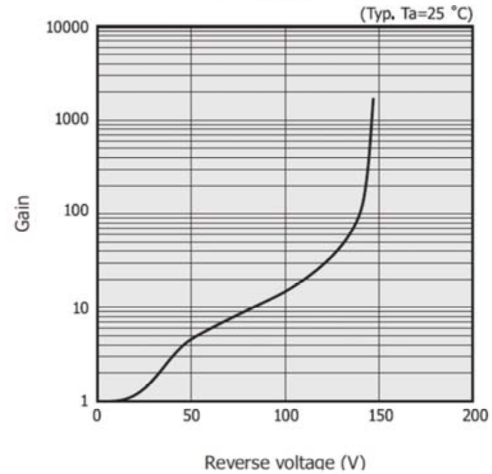

$$I_D = I_{ds} + MI_{dg} \quad (39)$$

The APD dark current consists of surface leakage current (Ids) that flows through the PN junction or oxide film interface and generated current (Idg) inside the substrate.

The surface leakage current is not multiplied because it does not pass through the avalanche layer, but the generated current is because it does pass through. Thus, th total dark current (I_D) is expressed be eq.(39).

The dark current gratly affects the noise characteristics.

## Gain vs. Reverse voltage characteristics

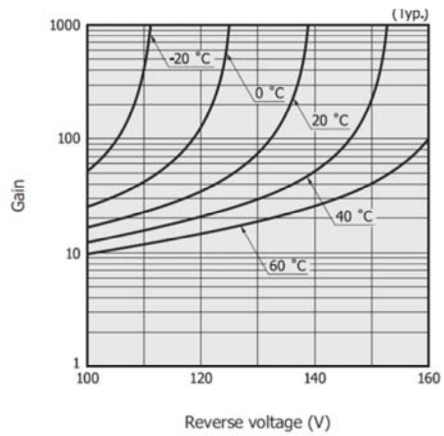



The APD gain is determined by the ionization rate, and the ionization rate depends strongly on the electric field across the depletion layer.

In the normal operating range, the APD gain increases as reverse voltage increases.

In the reverse voltage is increased even higher, the reverse voltage across the APD PN junction decreases due to the voltage drop caused by the series resistance component including the APD and circuit, and the gain begins to decrease.

## Temperature dependence of the gain




The APD gain has temperature dependent characteristics presented in the figure.

As the temperature rises, the crystal lattice vibrates more heavely, increasing the possibility that the accelerated carriers may collide with the lattice before reaching a sufficiently large energy level anf making it difficult for ionization to take place. Therefore, the gain at a certain reverse voltage becomes sall as the temperature rises.

To obtain a constant output, the reverse voltage must be adjusted to match changes in temperature or the element temperature must be kept constant.

# Performance parameter of APD

$$I_S = M \cdot R_0(\lambda) \cdot P_S \quad (40)$$

An avalanche photodiode, APD, differs from a PIN photodiode in that it provides internal amplification of the photoelectric signal.

The output signal current, Is, will be given by the relation (40), where R0 (λ) is the intrinsic responsivity of the APD to a gain M = 1 and the λ wavelength, and M is the gain of the avalanche photodiode and P is the optical incident power.

As we have seen, M gain is a function of the inverse voltage applied on diodes, VR.

# Noise in APD

$$I_n^2(APD) = 2q(I_L + I_{dg})M^2FB + 2qI_{ds}B \quad (41)$$

$$k = \frac{\beta}{\alpha} \quad (42)$$

$$F = kM + (1-k)(2-1/M) \quad (43)$$

$$F = k^{-1}M + (1-k^{-1})(2-1/M) \quad (44)$$

As long as the reverse voltage is constant, the APD gain is the average of each carrier's multiplication. The ionization rate of each carrier is not uniform and has statistical fluctuations.

Mulltiplication noise known as excess noise is therefore added during the multiplication process.

The APD shot noise (In) becomes larger than the PIN photodiode shot noise ans is expessed by equation (41), where:

q = electron charge

IL = photocurrent at M = 1

Idg = current generated inside the substrate (dark current component multiplied)

B = bandwidth

M = gain

F = excess noise factor

Ids = surface leakage current (dark current component not multiplied)

The ratio of the ionization rate of electrons (α) to the ionization ratio of holes (β) is called the ionization rate ratio [k, equation (42)]

The excess nose factor (F) can be expressed in terms of k as in equation (43). Equation (43) shows the excess noise factor when electrons are injected into the avalanche layer. To evaluate the excess noise factor when holes are injected into the avalanche layer, k is in equation (43) should be substituted by 1/k, and we obtain (44).

The excess noise has wavelength dependence .

## Signal-to-noise ratio and NEP in APD

$$\frac{S}{N} = \frac{I_L^2 M^2}{2q(I_L + I_{dg})FBM^2 + 2qI_{ds}B + \frac{4kTB}{R_L}} \quad (45)$$

$$NEP = \frac{I_n}{MR_0} \quad (46)$$

As explained, APD generates noise due to the multiplication process. So, excess noise increases with the gain increasing.

In the same time, the signal is also increased depending on the increase in gain.

Therefore there will be a gain for which the Signal-Noise ratio is maxim.

S / N for APD is given by relation (45), where:

2q (IL + Idg) BFM ^ 2 + 2qBIds = shot noise

(4kTB) / RL = thermal noise

k = Boltzman's constant

T = absolute temperature

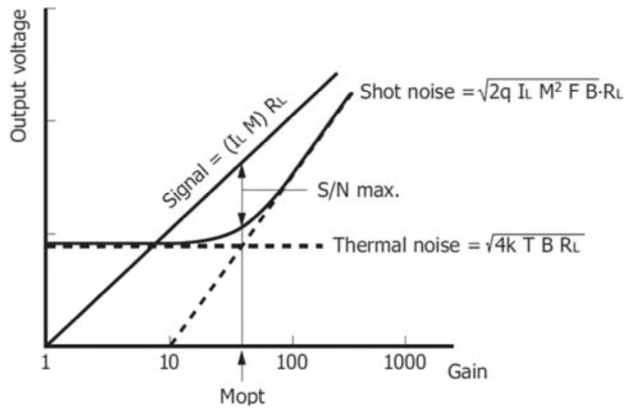
RL = load resistance

The equivalent noise power (NEP) of APD is given by the relationship (46), where:

M = gain

S = photosensitivity [A / W]

## Optimal gain M

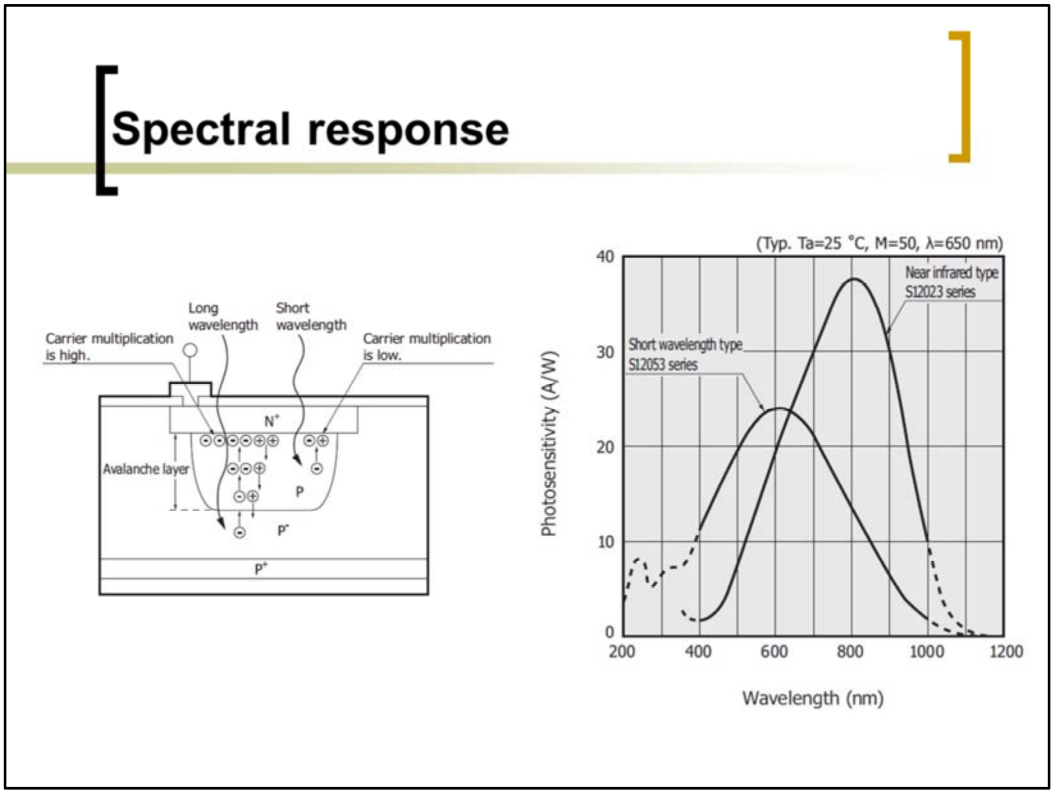



$$M_{opt} = \left[ \frac{4kT}{q\left(I_L + I_{dg}\right) R_L} \right]^{\frac{1}{2+x}} \qquad (47)$$

In the case of a PIN photodiode, using high load resistance reduces thermal noise but at the same time slows the response. It is therefore not practical to reduce thermal noise and in many cases, the lower limit of light detection is determined by thermal noise.

In the case of APD, the signal can be multiplied without the total noise increase until the shot noise reaches a level equal to the thermal noise. This means that using APD we can improve the S / N ratio while maintaining the speed of response. This behaviour is shown in the figure.

In this case, the optimum gain is obtained using the condition of maximizing the S / N ratio of the relationship (45). If we neglect Ids, the expression of optimal gain is given by the relationship (47).

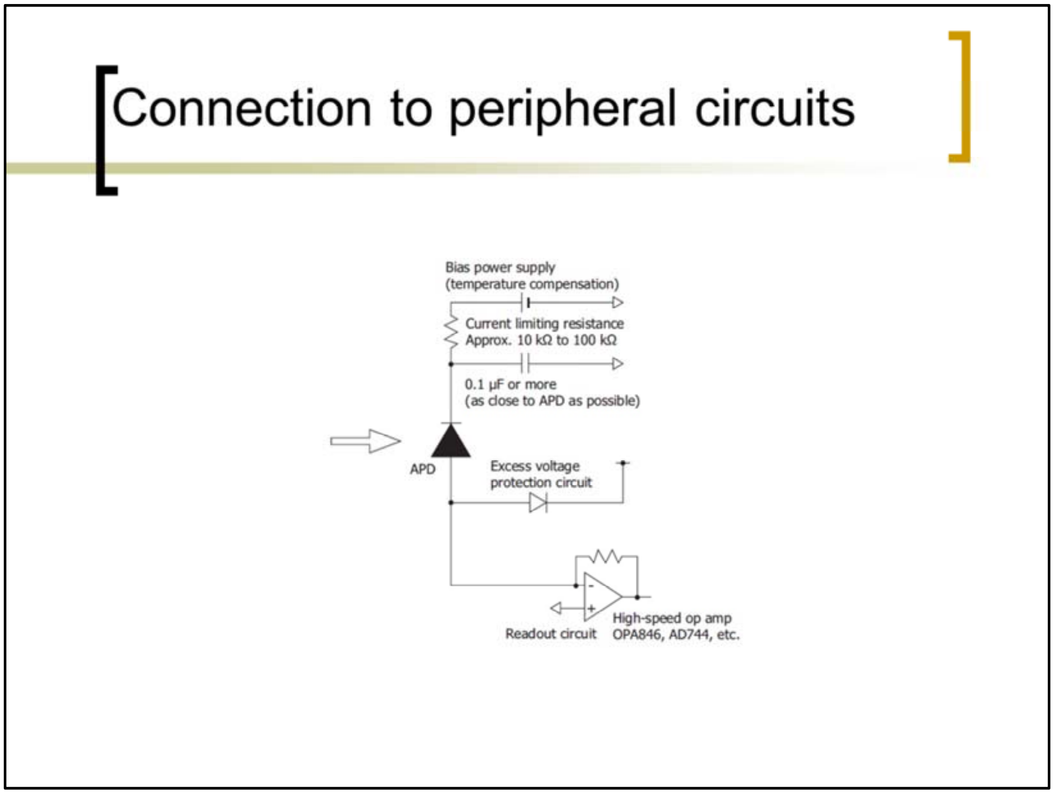



The spectral response of the APD is almost the same as with a conventional photodiode, unless a reverse voltage is applied to the diodes.

The depth at which light penetrates in the Si photodiode depends on the wavelength.

The depth at which short wavelengths penetrate is small, so carriers are generated near the surface.

By contrast, long-wavelength light generates carriers at greater depths.




APDs can be handled in the same manner as normal photodiodes except that a high reverse voltage is required.

However, the following precautions should be taken because APDs are operated at a high voltage, their gain changes depending on the ambient temperature, and so on.

1) APD power consumption is the product of the incident light level x sensitivity (M=1) x gain x reverse voltage, and it is considerably larger than that of PIN photodiodes. So there is a need to add a protective resistor between the APD and bias power supply and then install a current limiting circuit.
2) A low-noise readout circuit may damage the first stage in response to excess voltage. To prevent this, a protective circuit should be connected to divert any excess input voltage to the power supply voltage line.