TECHNICAL UNIVERSITY OF CLUJ-NAPOCA ROMANIA

Faculty of Electronics, Telecom and Info Technology

Lecture 8

Optoelectronic Sensors with Industrial Applications

Receivers

Associate prof Ramona Galatus
Basis of Electronics Department

Outline: Detectors and Receivers

- Describe the basic operation of a photodiode.
- Describe the operation of a PIN photodiode.
- Describe the operation of an Avalanche Photodiode (APD).
- Describe the performance characteristics of commonly used photodiodes.
- Describe the basic components in a fiber optic receiver.
- Describe receiver performance characteristics.

Receivers: Photodetectors in telecommunication

- For data interpretation
- Depending on how sophisticated the receiving and associated signal processing functions are in the receiver, these electronics can range from
    - some simple amplification functions for relatively strong, clean signals to
    - hordes of complex circuitry if the receiver needs to interpret weak, distorted signals at high data rates.
- performance characteristics
- Random noises/ SIGNAL-TO-NOISE RATIO
- probability of errors occurring in a data stream

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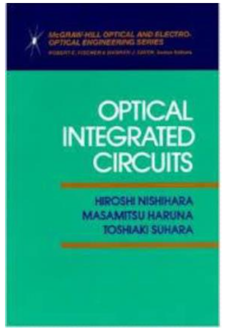
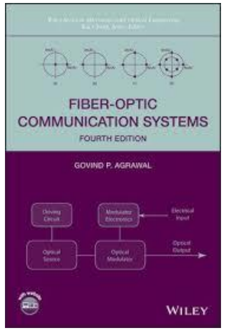
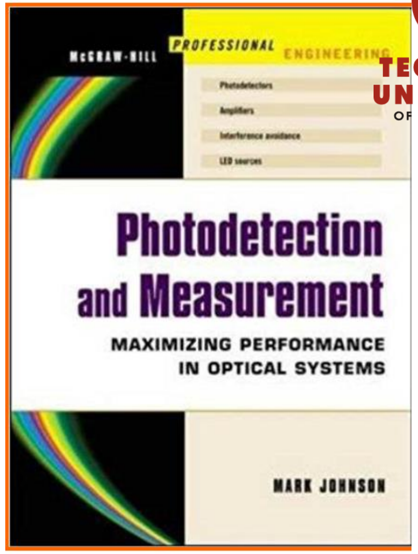
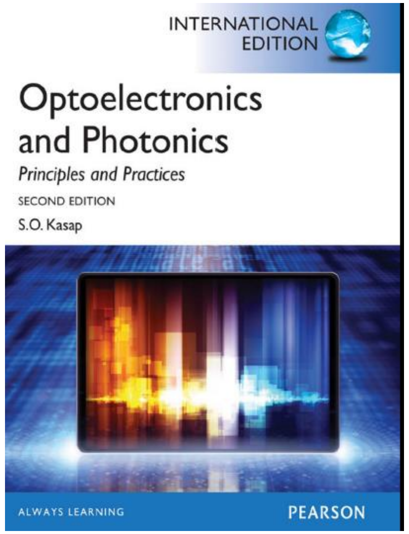
References

Bahaa Saleh – cap 17









Introduction

What does ‘detecting light’ mean?

- Turn an ‘optical signal’ into an ‘electrical signal’ (current or voltage) that is easy to work with (amplify, process, digitize, …)
- Convert
    - energy in the electromagnetic field associated with the optical signal into electrical energy
    - energy carried by photons into electrical charge carriers
- Typically done using ‘photodetectors’
- In this lecture we focus on ‘photodiodes’ and ‘solar cells’

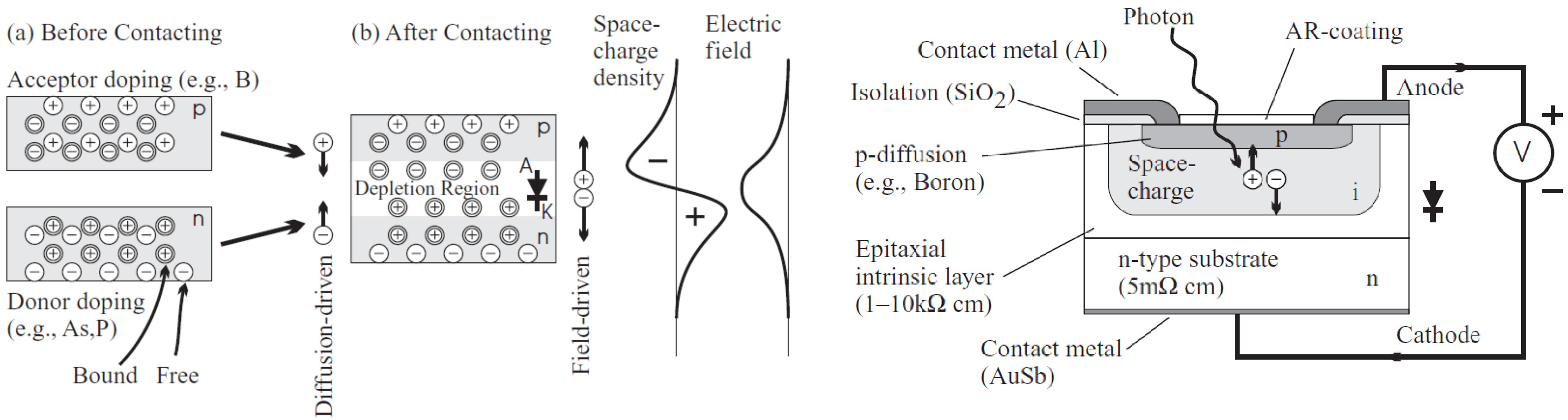
Photodetector

- converts the variation of the optical power to a correspondingly varying electric current

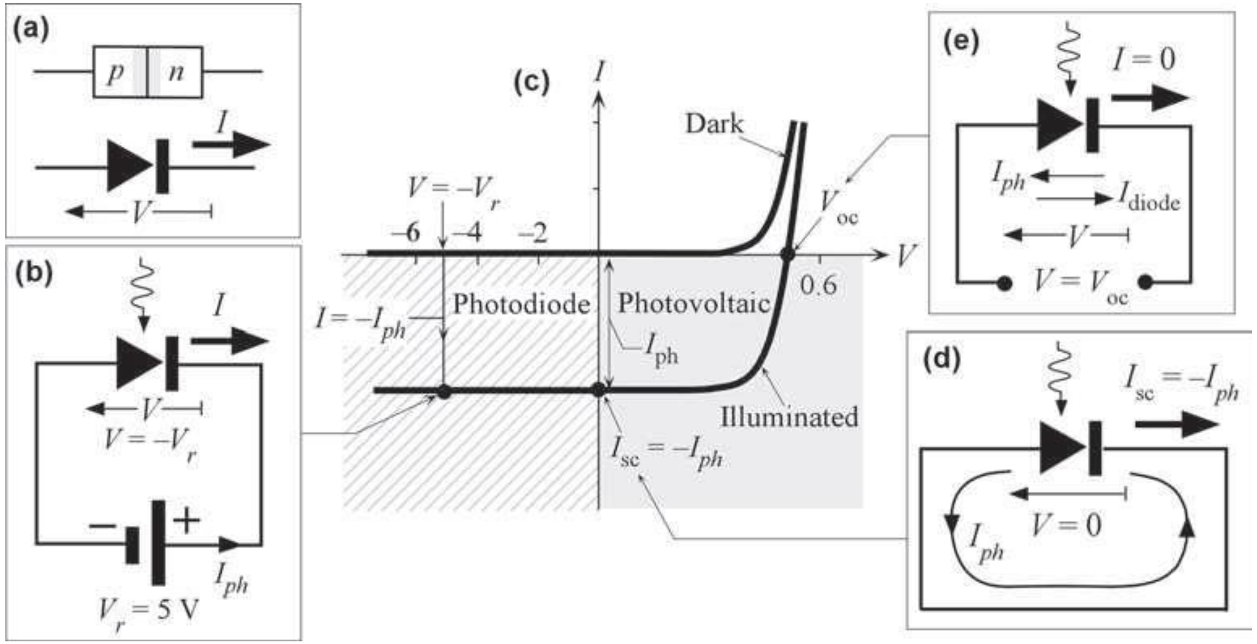
- **Perfomances:**
- A high sensitivity to the emission wavelength range of the received light signal
- A minimum addition of noise to the signal
- A fast response speed to handle the desired data rate
- Be insensitive to temperature variations
- Be compatible with the physical dimensions of the fiber/ in case of optical fiber sensors
- Have a reasonable cost compared to that of other system components
- Have a long operating lifetime

- Types
- PIN (*n*-doped intrinsic (*i*) region)
- APD (avalanche photodiode)

PN Junction and real structure



I-V diagram



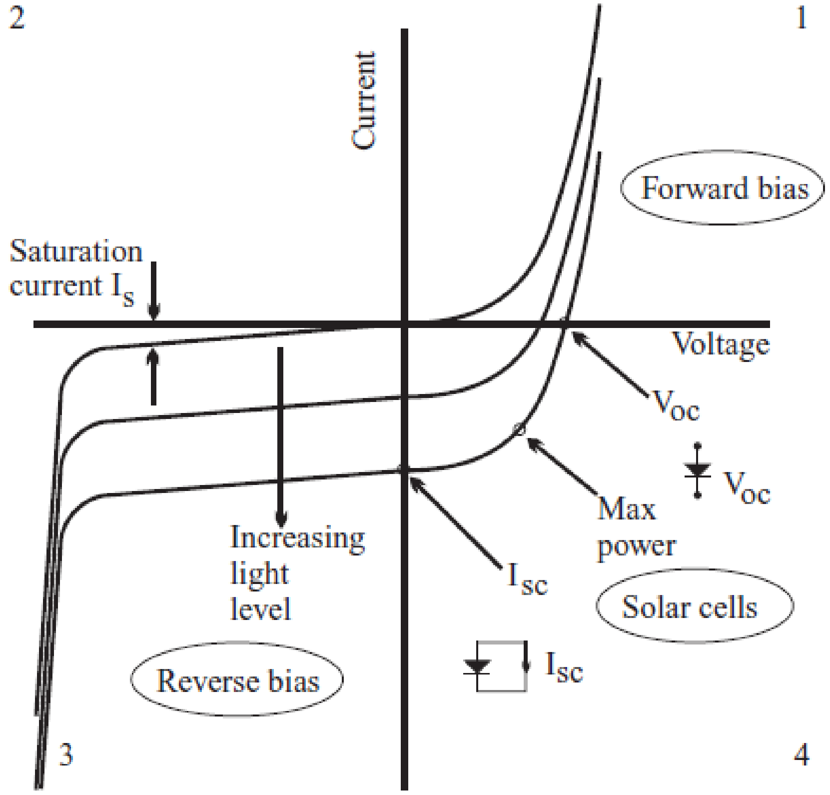
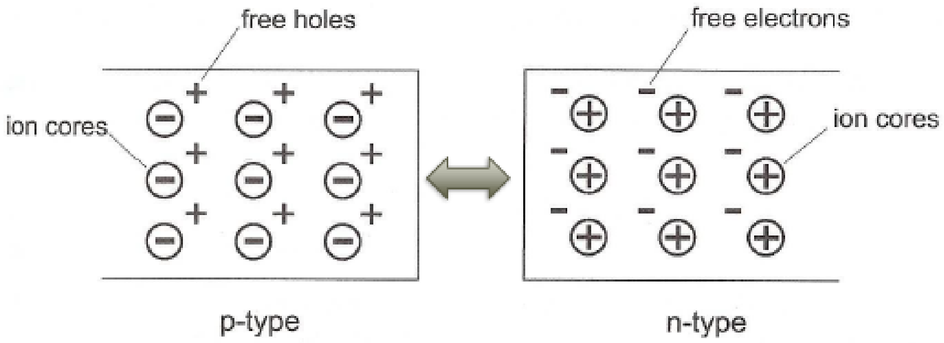


Figure 4.4 Photodiode IV characteristic. Photodetection is possible in quadrants 1, 3, 4.

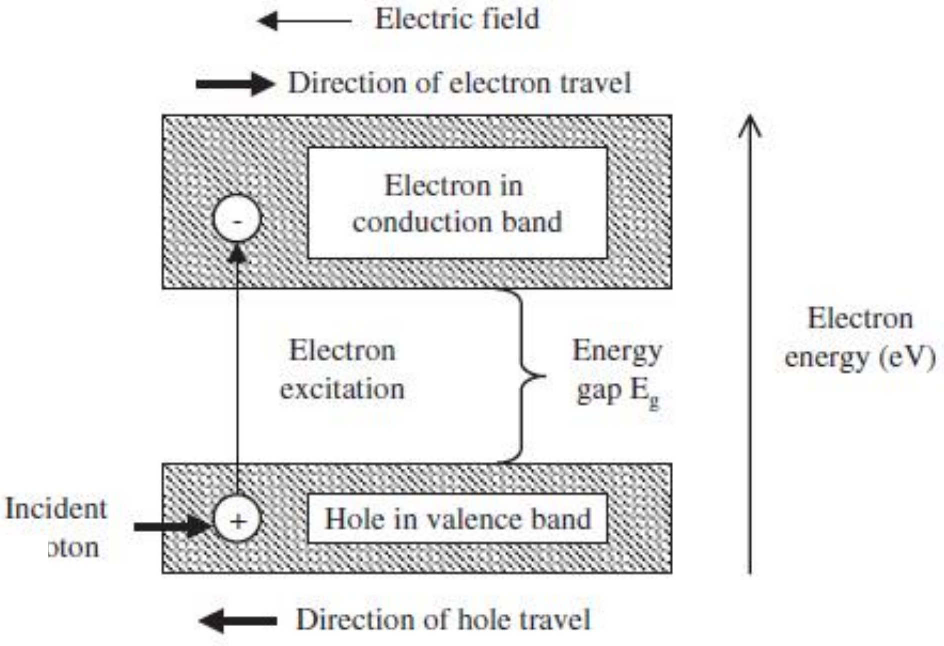
P-n junction=> PIN junction

Structure

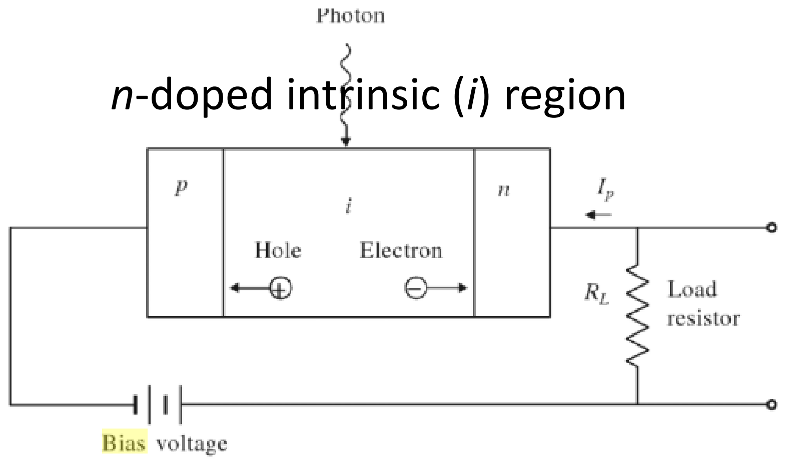
– Bring a piece of p-type Si in contact with a piece of n-type Si
  ➔ formation of a diode



$$\lambda_c = \frac{hc}{E_g} = \frac{1.240}{E_g}$$



n-doped intrinsic (*i*) region



An incident photon is able to boost an electron to the conduction band only if it has an energy that is greater than or equal to the bandgap energy.

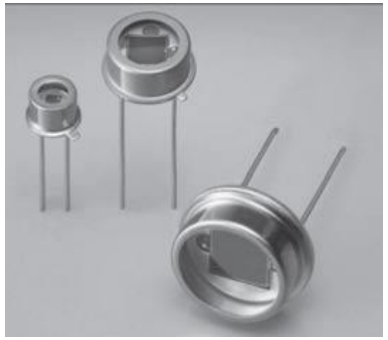
Cuttoff wavelength λ_c

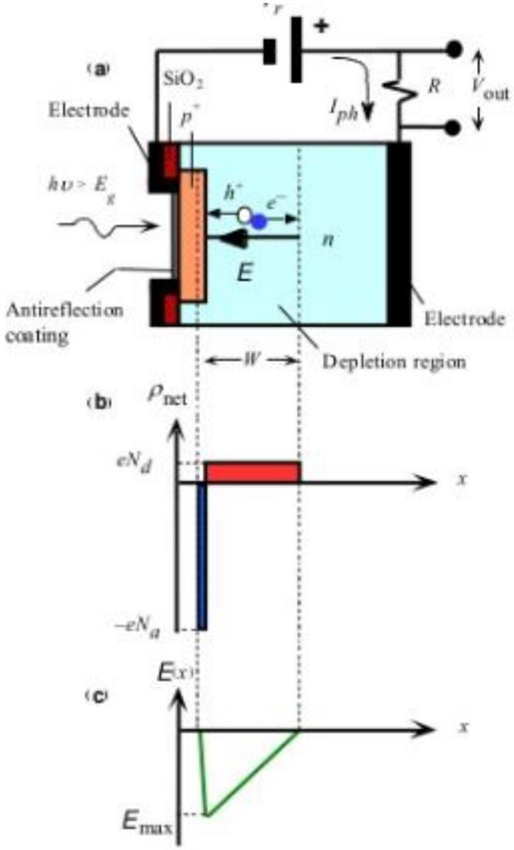
beyond a certain wavelength, the light will not be absorbed by the material since the wavelength of a photon is inversely proportional to its energy. The longest wavelength at which this occurs is called the *cutoff wavelength*

Photocarriers-> photocurrent

Schematic of a *pin* photodiode circuit with an applied reverse bias.

PN Photodiode





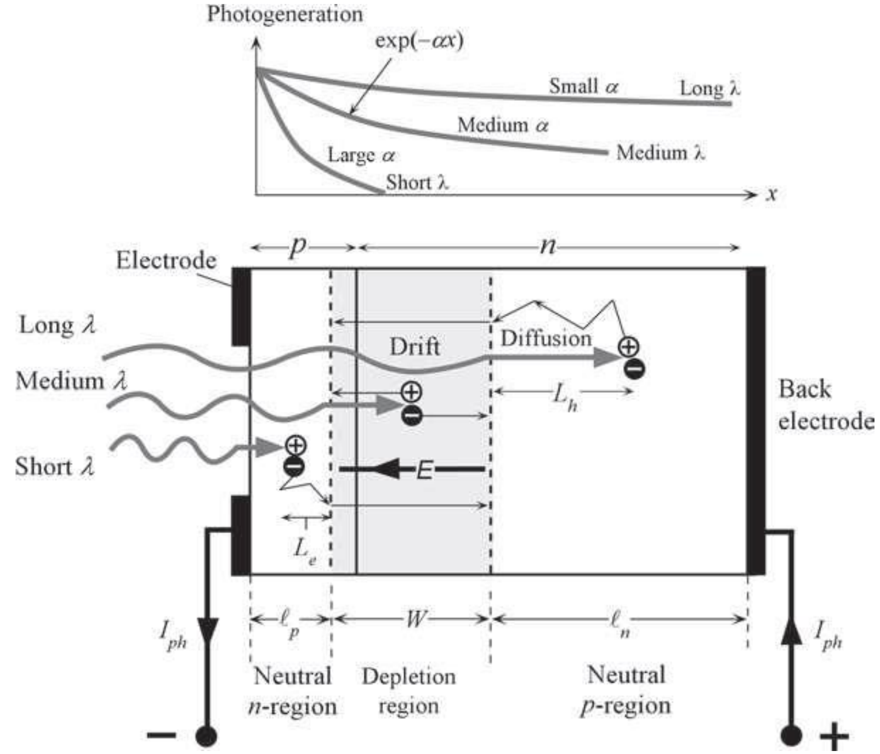
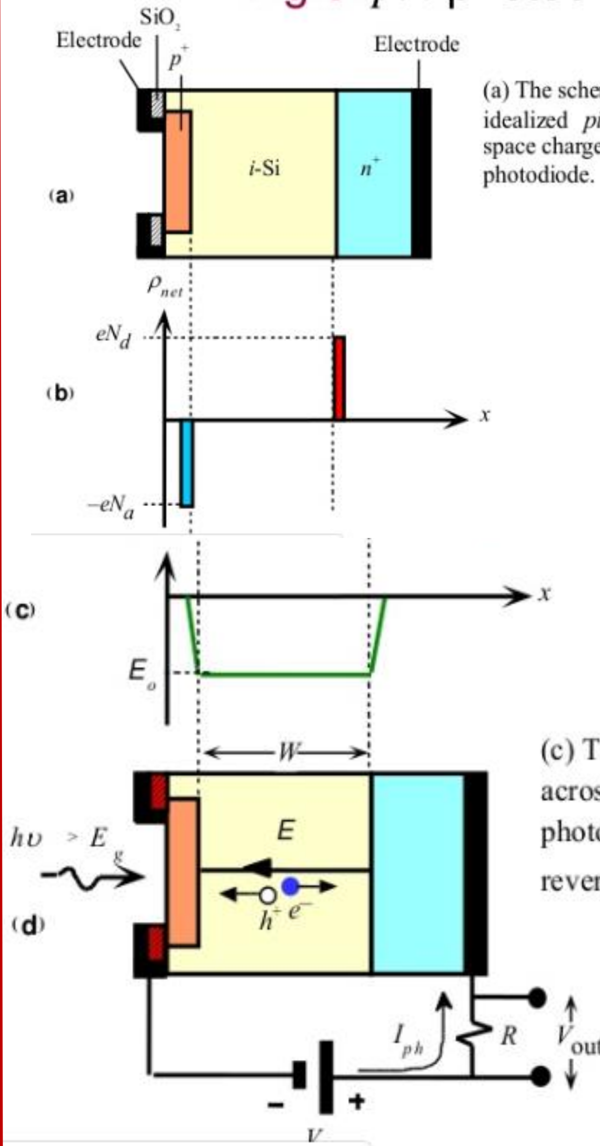


Fig.1: *pn*-junction photodiode

(a) A schematic diagram of a reverse biased *pn* junction photodiode. (b) Net space charge across the diode in the depletion region. N_d and N_a are the donor and acceptor concentrations in the *p* and *n* sides. (c). The field in the depletion region.

PIN Photodiode

Fig.3: *pin* photodiode



(a) The schematic structure of an idealized *pin* photodiode (b) The net space charge density across the photodiode.

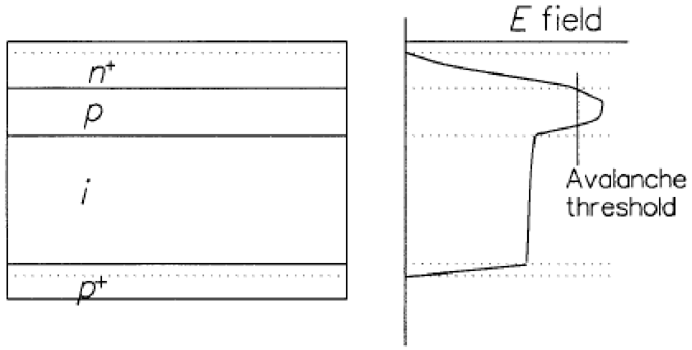
(c) The built-in field across the diode. (d) The *pin* photodiode in photodetection is reverse biased.

APD photodiode

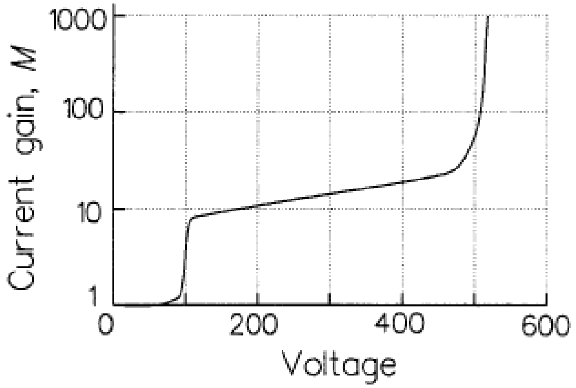
$$\mathcal{R}_{APD} = \frac{\eta q \lambda}{hc} M = \mathcal{R}_0 M$$

$$M = \frac{I_M}{I}$$

- With the APD, a small bundle of photons can trigger an avalanche of electrons. The APD accomplishes this through a process called *photomultiplication*



Structure of avalanche photodetector



Bias voltage

The APD is constructed with one more *P* region than the PIN photodiode, as shown in Figure
When the APD is biased very close to its breakdown voltage, it acts like an amplifier with a multiplication factor, or *gain (M) –(non-dimensional value)*
An APD with a multiplication factor of 50 sets free on the average 50 electrons for each photon absorbed. The free electrons produce current flow through the electrical circuit connected to the APD.

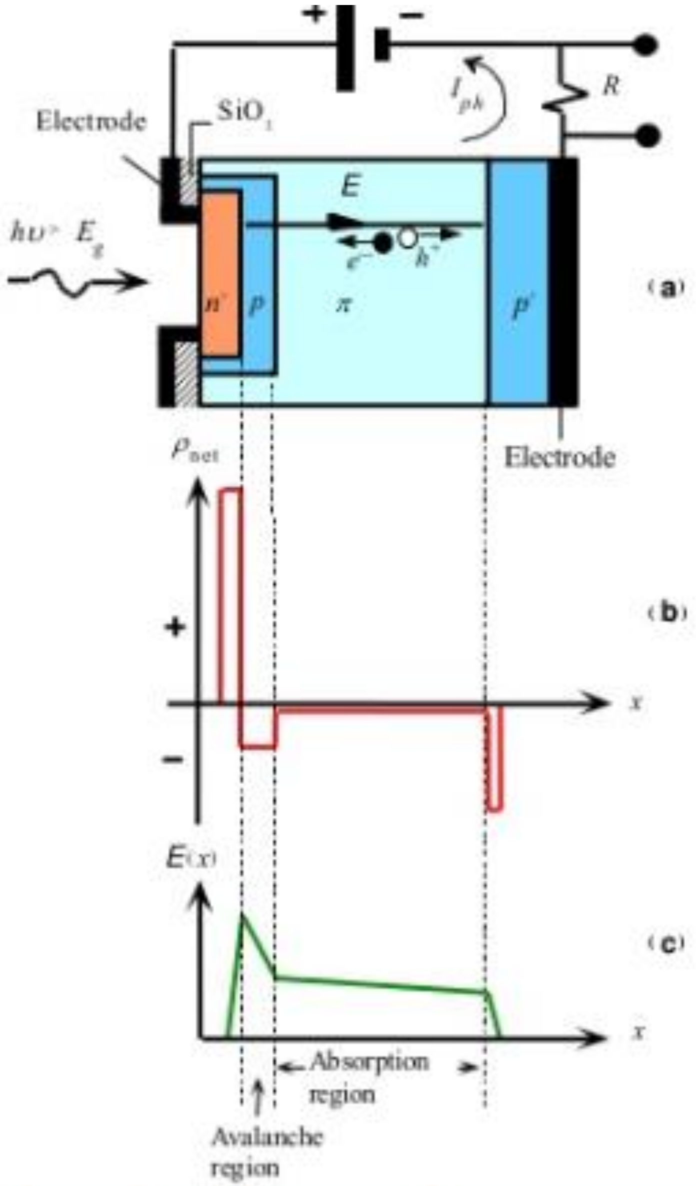


Fig.5: Avalanche Photodiode

(a) A schematic illustration of the structure of an avalanche photodiode (APD) biased for avalanche gain. (b) The net space charge density across the photodiode. (c) The field across the diode and the identification of absorption and multiplication regions.

P-n junction

D. Diode I-V characteristic

Shockley diode equation

$$\boxed{i = i_0\left[e^{\frac{eV}{\beta k_B T}} - 1\right]}$$

$e = 1.61 \times 10^{-19} C$
$k_B = 1.38 \times 10^{-23} J \cdot K^{-1}$
Boltzmann

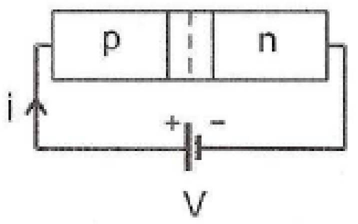
Diode current

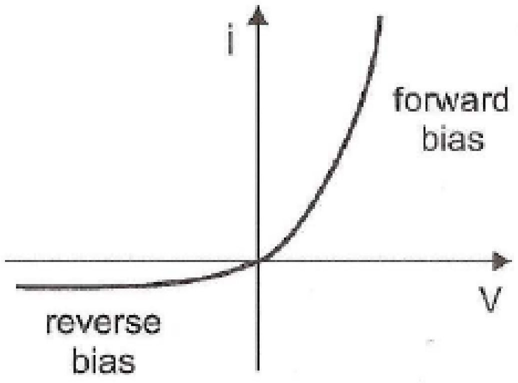
Saturation current

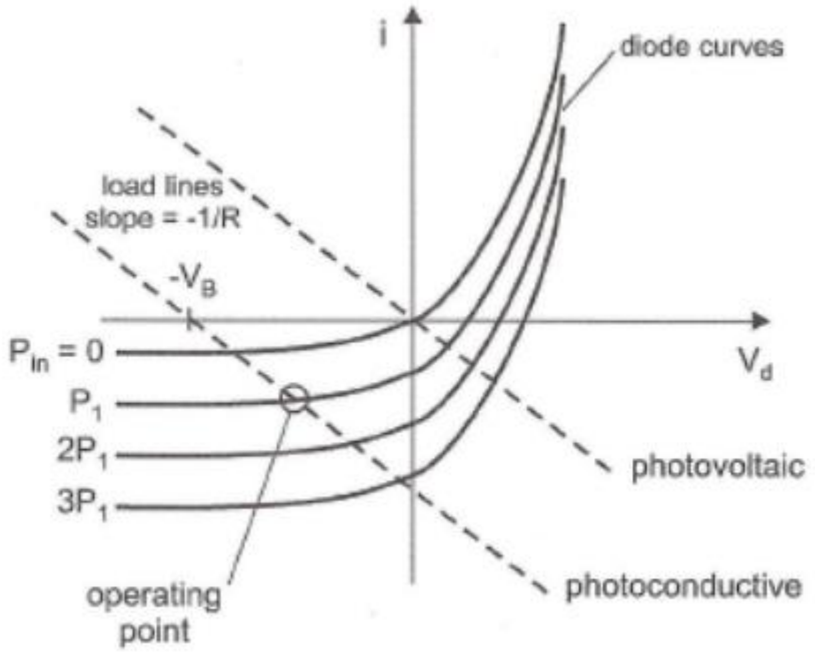
Diode ideality factor

↓

Total hole and electron current



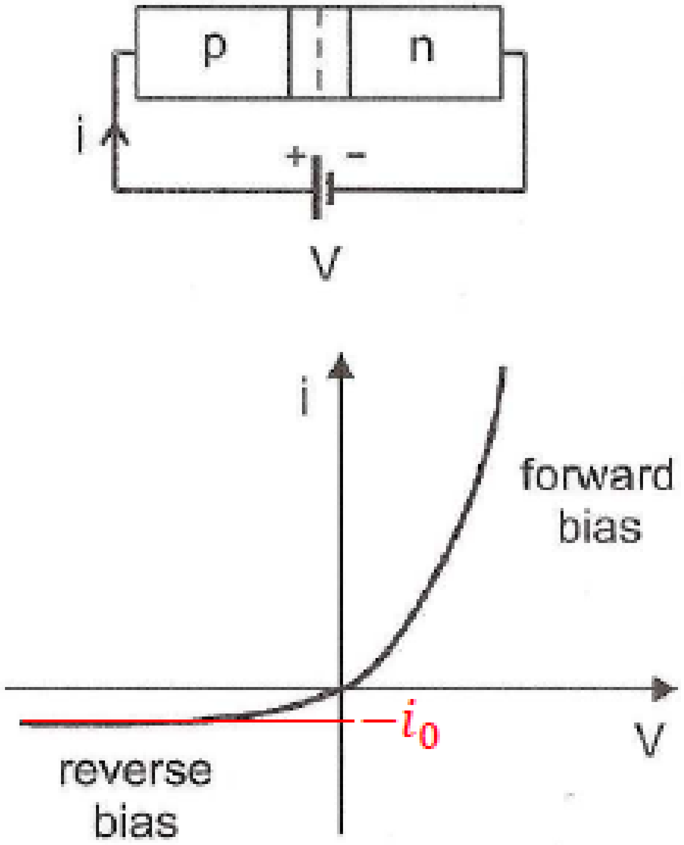




– Reverse saturation current i_0 is current under large reverse bias V such that $eV \ll -k_B T$ and $i \cong -i_0$
➔ result of thermal generation of electron-hole pairs in and near depletion region with probability proportional to

$$e^{-E_g/k_B T}$$

➔ $i_0 \div e^{-E_g/k_B T}$
➔ increases with temperature

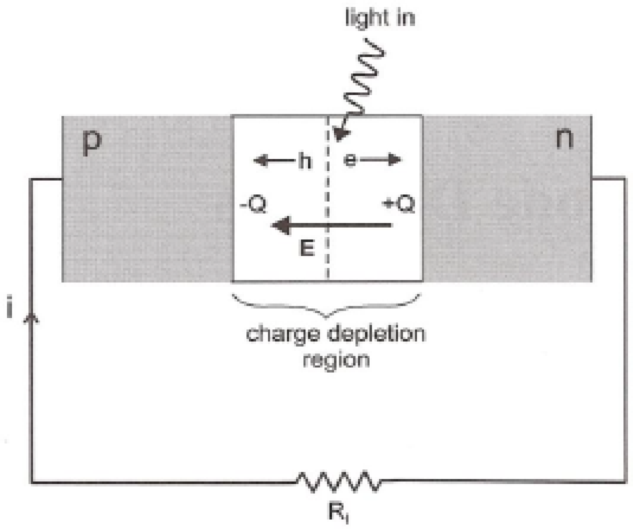


"illuminated" p-n junction

A. Principle of operation

– Light incident on a pn-junction can be absorbed to generate electron-hole pairs
➔ motion of electrons and holes in depletion regions causes a current
➔ appearance of a 'photocurrent' i_λ
➔ total diode current

$$\boxed{i = i_0\left[e^{\frac{eV_d}{\beta k_B T}} - 1\right] - i_\lambda}$$



Convention: diode current is taken positive when entering the p-side
➔ photocurrent i_λ is negative

“illuminated” p-n junction

B. The photocurrent

- The photocurrent is the diode current generated by an incident stream of photons

$$i_\lambda = N \cdot \eta_{abs} \cdot e$$

N: $\frac{\#\ incident\ photons}{second}$

e: $1\ absorbed\ photon \rightarrow 1\ charge$

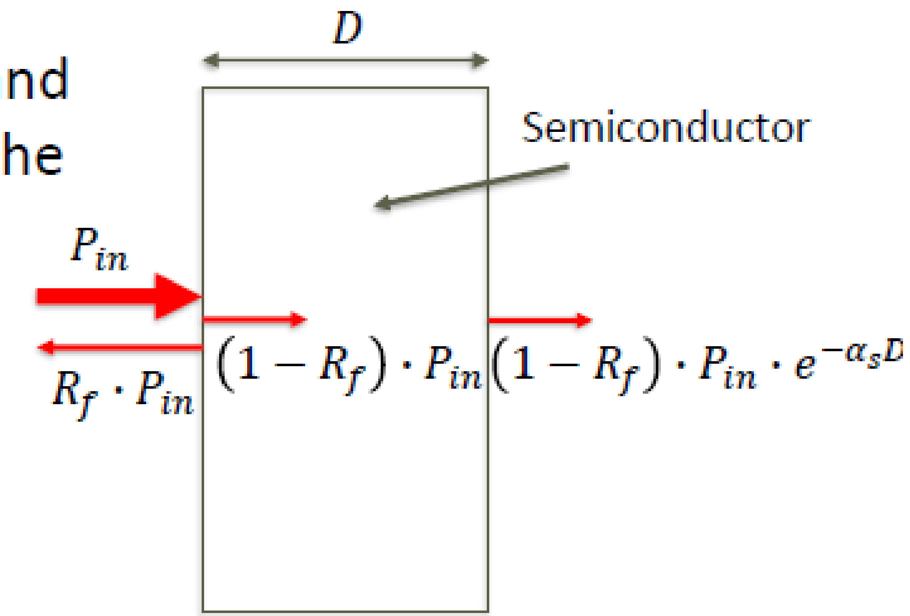
η_{abs}: $$Absorption\ efficiency = \frac{\#\ absorbed\ photons}{\#\ incident\ photons}$$

$$\boxed{\Rightarrow i_\lambda = \frac{P_{in}}{h\nu} \cdot \eta_{abs} \cdot e}$$

h-Plank constant

- The absorption efficiency η_{abs} depends on the absorption coefficient α_s and on the refractive index of the semiconductor

$$\eta_{abs} = \frac{P_{abs}}{P_{in}}$$



$$\Rightarrow \eta_{abs} = \frac{(1 - R_f) \cdot P_{in} - (1 - R_f) \cdot P_{in} \cdot e^{-\alpha_s D}}{P_{in}}$$

$$\Rightarrow \eta_{abs} = (1 - R_f) \cdot (1 - e^{-\alpha_s D})$$

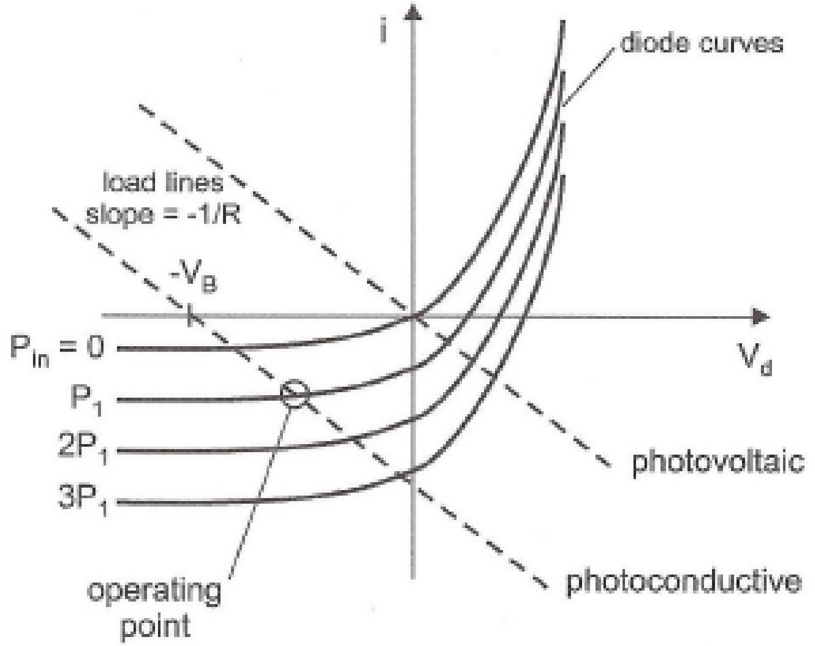
$$\boxed{\Rightarrow i_\lambda = \frac{e}{h\nu} \cdot P_{in} \cdot (1 - R_f) \cdot (1 - e^{-\alpha_s D})}$$

Depends on refractive index

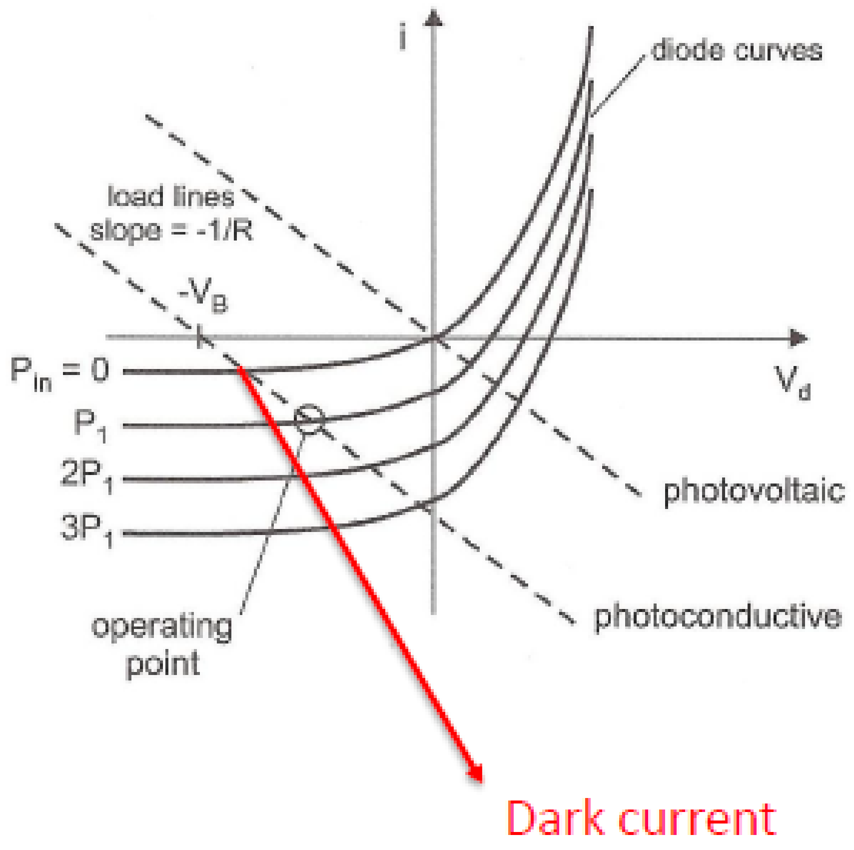
D. Illuminated diode I-V characteristic

- Diode I-V characteristic is shifted downwards due to i_λ
  ➔ the larger P_{in} the lower the curve
- The 'operating point' provides the values of i and V_d
  ➔ expresses that must satisfy two equations

$$\begin{cases} i = -\dfrac{1}{R}(V_d + V_B) \\ i = i_0\left[e^{\frac{eV_d}{\beta k_B T}} - 1\right] - i_\lambda \end{cases}$$



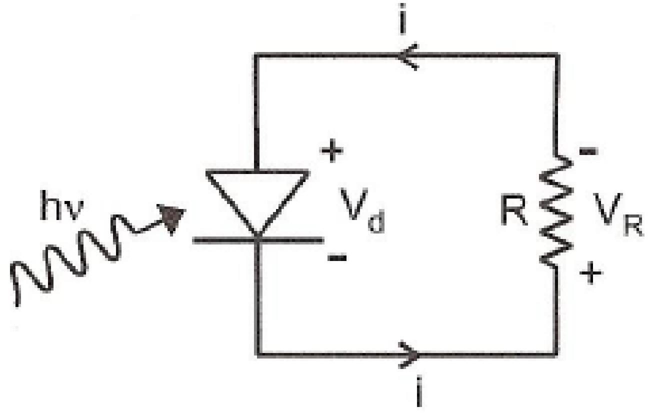
- Photovoltaic mode
  - Operating point at $i = 0$ for $P_{in} = 0$
    ➔ higher sensitivity and less noisy for low light level detection than photoconductive mode
  - Used for solar cells
- Photoconductive mode
  - Operating point at $i = -i_0$ for $P_{in} = 0$
    ➔ existence of 'dark current'
  - Faster response time $\tau = RC$ as capacitance is lower due to larger width of depletion layer
  - More linear response over wide range of light intensities



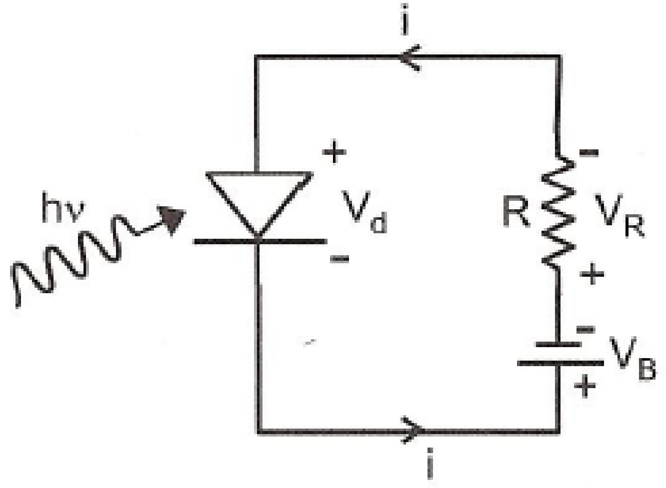
Modes of Operation (Photoconductive vs. Photovoltaic)
A photodiode can be operated in one of two modes: photoconductive (reverse bias) or photovoltaic (zero-bias). Mode selection depends upon the application's speed requirements and the amount of tolerable dark current (leakage current).

C. Photovoltaic and photoconductive scheme

- Photovoltaic – load resistor R directly connected across the pn-diode



- Photoconductive – load resistor R in series with reverse bias voltage V_B



$$V_d + V_R + V_B = 0$$

$$\Rightarrow V_d + iR + V_B = 0$$

$$\Rightarrow i = -\frac{1}{R}(V_d + V_B) = i_0\left[e^{\frac{eV_d}{\beta k_B T}} - 1\right] - i_\lambda$$

Operations mode

Photoconductive

In photoconductive mode, an external reverse bias is applied. The current measured through the circuit indicates illumination of the device; the measured output current is linearly proportional to the input optical power. Applying a reverse bias increases the width of the depletion junction producing an increased responsivity with a decrease in junction capacitance and produces a very linear response. Operating under these conditions does tend to produce a larger dark current, but this can be limited based upon the photodiode material. (https://www.thorlabs.com/tutorials.cfm?tabID=31760)

Photovoltaic

In photovoltaic mode the photodiode is zero biased. The flow of current out of the device is restricted and a voltage builds up. This mode of operation exploits the photovoltaic effect, which is the basis for solar cells. The amount of dark current is kept at a minimum when operating in photovoltaic mode.

Dark Current

Dark current is leakage current that flows when a bias voltage is applied to a photodiode. When operating in a photoconductive mode, there tends to be a higher dark current that varies directly with temperature. Dark current approximately doubles for every 10 °C increase in temperature, and shunt resistance tends to double for every 6 °C rise. Of course, applying a higher bias will decrease the junction capacitance but will increase the amount of dark current present.

The dark current present is also affected by the photodiode material and the size of the active area. Silicon devices generally produce low dark current compared to germanium devices which have high dark currents.

The table below lists several photodiode materials and their relative dark currents, speeds, sensitivity, and costs.

Material	Dark Current	Speed	Spectral Range	Cost
Silicon (Si)	Low	High Speed	Visible to NIR	Low
Germanium (Ge)	High	Low Speed	NIR	Low
Gallium Phosphide (GaP)	Low	High Speed	UV to Visible	Moderate
Indium Gallium Arsenide (InGaAs)	Low	High Speed	NIR	Moderate
Indium Arsenide Antimonide (InAsSb)	High	Low Speed	NIR to MIR	High
Extended Range Indium Gallium Arsenide (InGaAs)	High	High Speed	NIR	High
Mercury Cadmium Telluride (MCT, HgCdTe)	High	Low Speed	NIR to MIR	High

Junction Capacitance

Junction capacitance (C_j) is an important property of a photodiode as this can have a profound impact on the photodiode's bandwidth and response. It should be noted that larger diode areas encompass a greater junction volume with increased charge capacity. In a reverse bias application, the depletion width of the junction is increased, thus effectively reducing the junction capacitance and increasing the response speed.

Bandwidth and Response

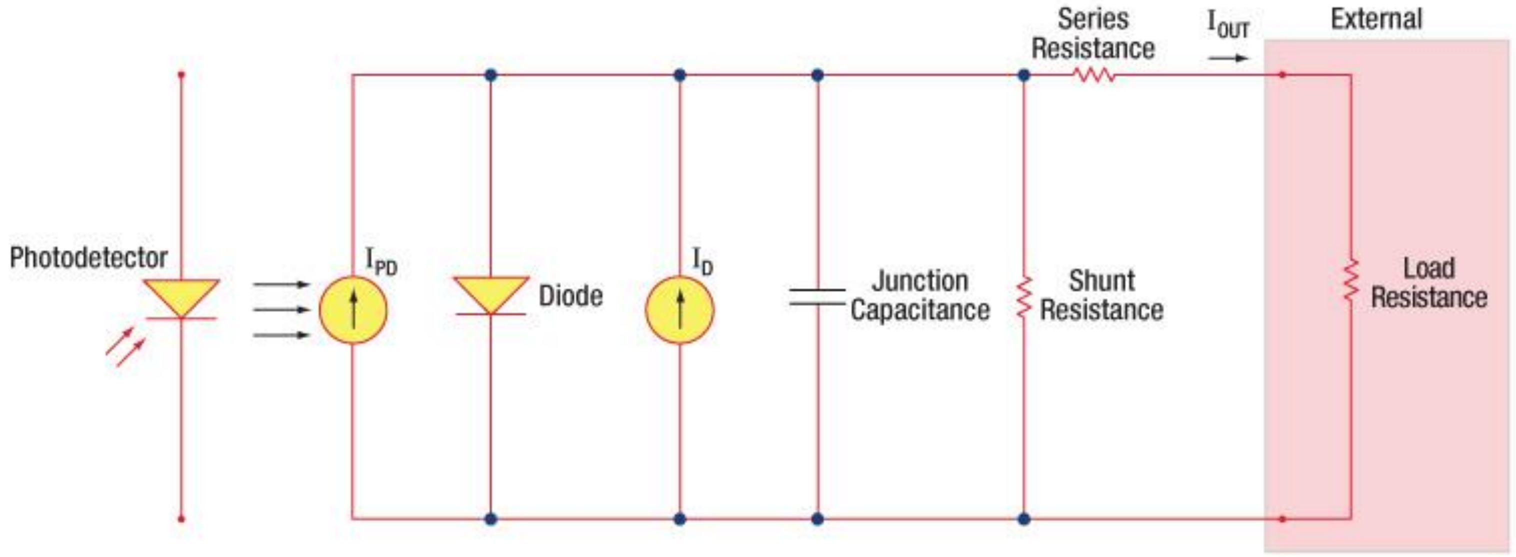
A load resistor will react with the photodetector junction capacitance to limit the bandwidth. For best frequency response, a 50 Ω terminator should be used in conjunction with a 50 Ω coaxial cable. The bandwidth (f_{BW}) and the rise time response (t_r) can be approximated using the junction capacitance (C_j) and the load resistance (R_{LOAD}):

$$f_{BW} = 1 / (2 * \pi * R_{LOAD} * C_j)$$

$$t_r = 0.35 / f_{BW} \quad \text{(rise time)}$$

Referece: https://www.thorlabs.com/tutorials.cfm?tabID=31760

Equivalent circuit



$$I_{OUT} = I_{DARK} + I_{PD}$$

junction photodiode is an intrinsic device that behaves similarly to an ordinary signal diode, but it generates a photocurrent when light is absorbed in the depleted region of the junction semiconductor. A photodiode is a fast, highly linear device that exhibits high quantum efficiency based upon the application and may be used in a variety of different applications.

Performance: Adsorption of light in semiconductors

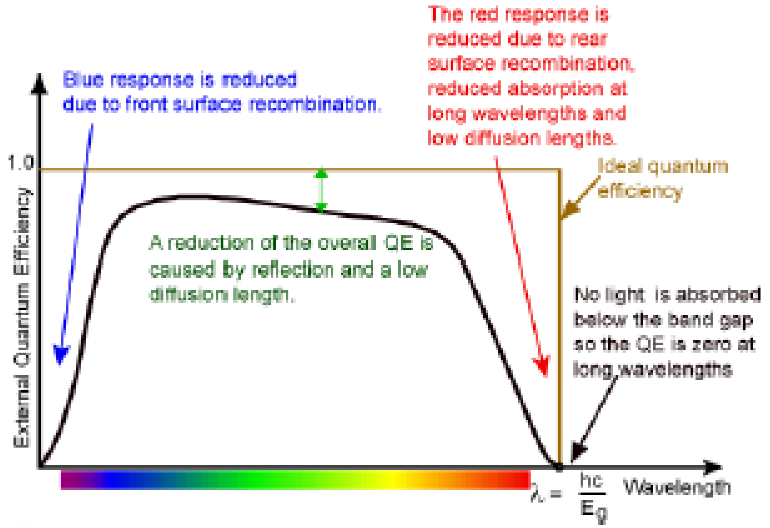
A. Quantum efficiency

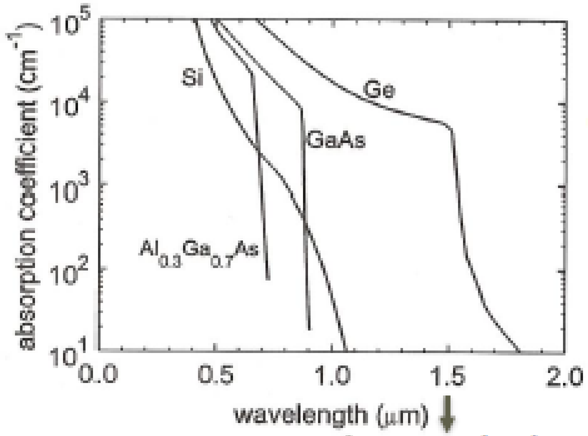
- The 'external' quantum efficiency is the number of collected electrons per incident photon of energy $h\nu$

$$\eta = \frac{\#collected\ electrons}{\#incident\ photons\ with\ energy\ h\nu}$$

$$\Rightarrow \eta = \frac{i_\lambda/_e}{P_{in}/_{h\nu}}$$

- Quoted at 1 wavelength
- Determined by
  - the absorption coefficient
  - the thickness of the depletion layer
  - 'optical loss' mechanisms such as reflection at interfaces
  - 'electronic loss' mechanisms such as recombination of carriers
- Typical value of 30 to 95%





Cut-off wavelength

$$\lambda_c = \frac{1.24}{E_g\ (in\ eV)}\ \mu m$$

$\boldsymbol{\lambda_c(Ge) = 1.6\ \mu m}$

$\boldsymbol{\lambda_c(Si) = 1.06\ \mu m}$

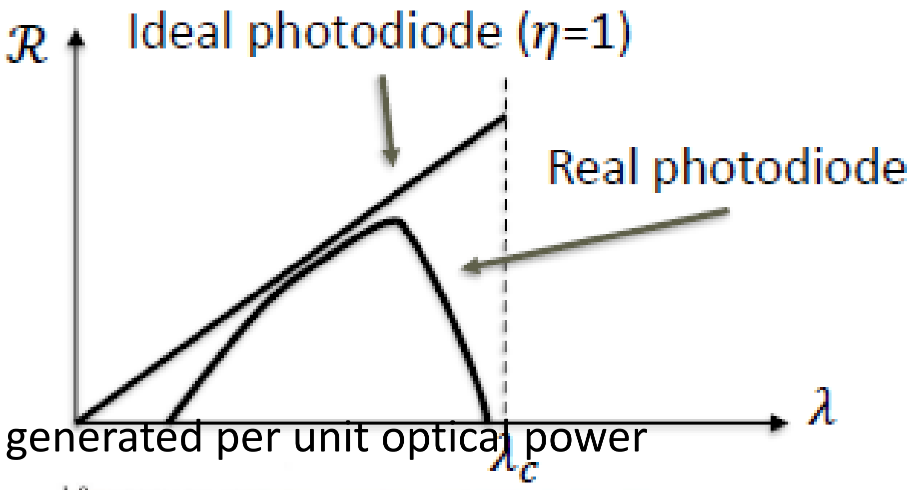
Performance: Adsorption of light in semiconductors

B. Responsivity

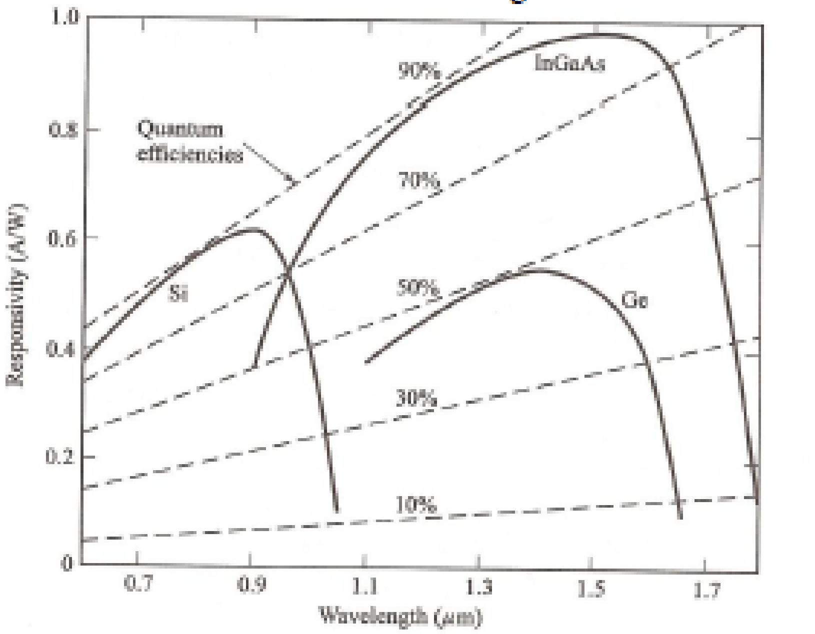
- Characterizes the performance of a photodiode

$$\mathcal{R} = \frac{Photocurrent}{Incident\ optical\ power}$$

$$\Rightarrow \mathcal{R} = \frac{i_\lambda}{P_{in}} = \frac{\eta e}{h\nu} = \frac{\eta e \lambda}{hc}$$

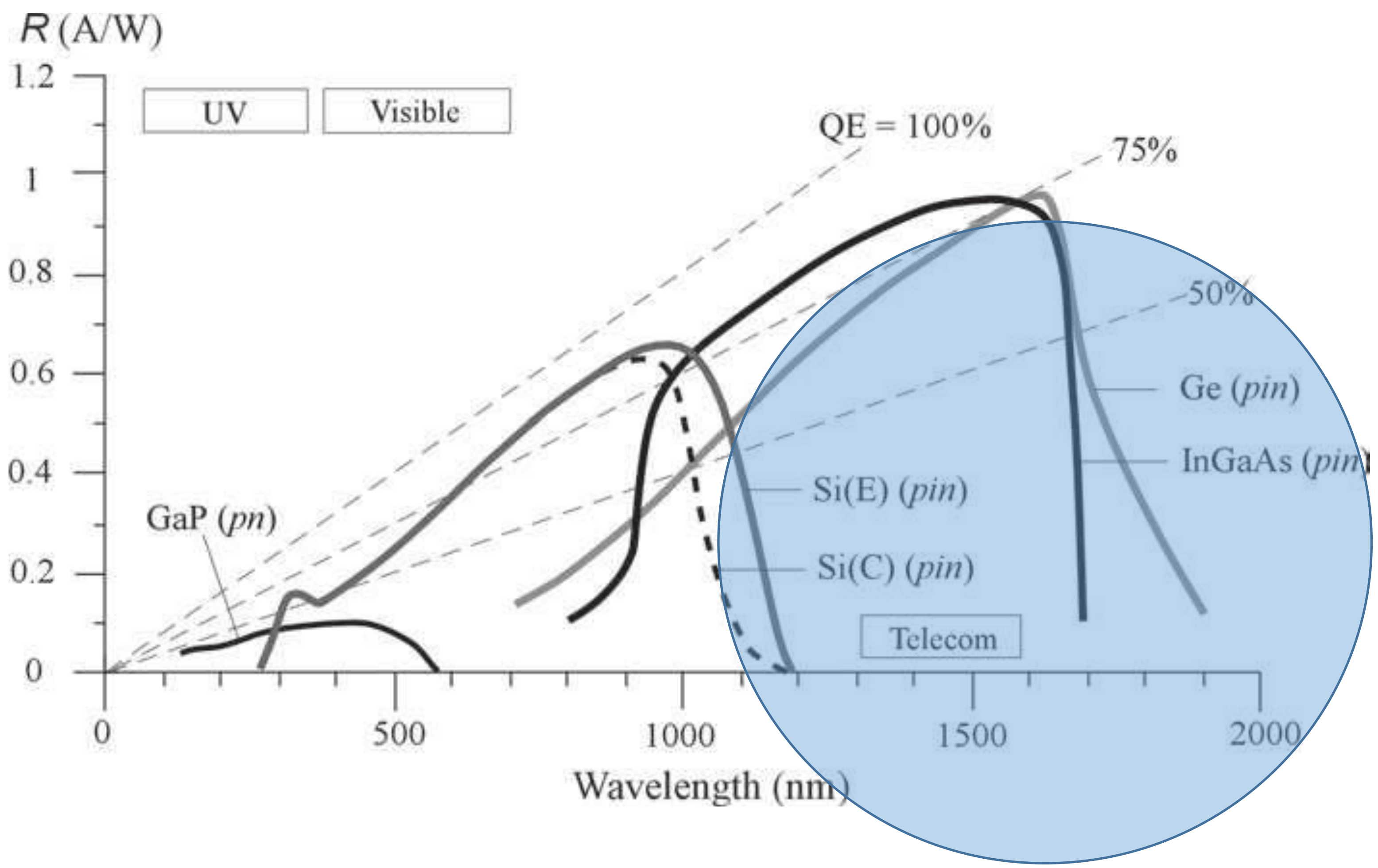


photocurrent generated per unit optical power



- Expressed in Ampère per Watt (A/W)
- Typical values
  - Si 0.65 A/W at 900 nm
  - Ge 0.45 A/W at 1300 nm
  - InGaAs 1.0 A/W at 1550 nm

Responsivity comparison



Semiconductor	Wavelength [nm]	Responsivity [A/W]	Dark current [nA]	Rise time [ns]
Si	850 – 950	0.60 – 0.80	10	0.07
Ge	1000 – 1500	0.45	1000	1.0 – 2.0
InGaAs	1310 – 1550	0.85	0.5 – 1.0	0.005 – 5.0

Material	Energy gap, eV	λ_{cutoff}, nm	Wavelength range, nm
Silicon	1.17	1060	400–1060
Germanium	0.775	1600	600–1600
GaAs	1.424	870	650–870
InGaAs	0.73	1700	900–1700
InGaAsP	0.75–1.35	1650–920	800–1650

Generic operation parameters for pin

Parameter	Symbol	Unit	Si	Ge	InGaAs
Wavelength range	λ	nm	400–1100	800–1650	1100–1700
Responsivity	$\mathcal{R}$	A/W	0.4–0.6	0.4–0.5	0.75–0.95
Dark current	I_D	nA	1–10	50–500	0.5–2.0
Rise time	τ_r	ns	0.5–1	0.1–0.5	0.05–0.5
Bandwidth	B	GHz	0.3–0.7	0.5–3	1–2
Bias voltage	V_B	V	5	5–10	5

Generic operation parameters for APD

Parameter	Symbol	Unit	Si	Ge	InGaAs
Wavelength range	λ	nm	400–1100	800–1650	1100–1700
Avalanche gain	M	—	20–400	10–200	10–40
Dark current	I_D	nA	0.1–1	50–500	10–50 @ M = 10
Rise time	τ_r	ns	0.1–2	0.5–0.8	0.1–0.5
Gain × bandwidth	$M \cdot B$	GHz	100–400	2–10	20–250
Bias voltage	V_B	V	150–400	20–40	20–30

Response speed

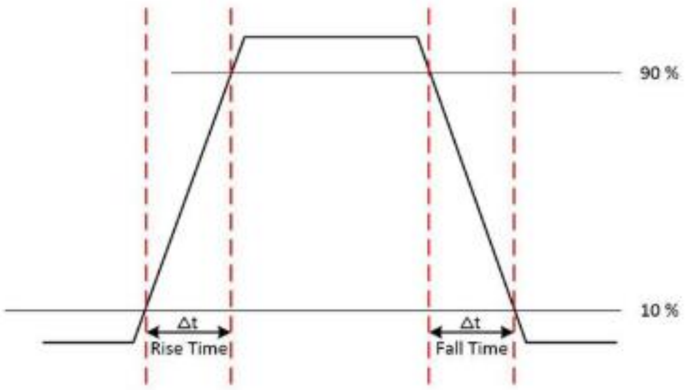
- Photodiodes need to have a fast response speed in order to properly interpret high data rate signals. If the detector output does not track closely the variations of the incoming optical pulse shape, then the e distorted

RISE TIME

Time for the signal to go from 10% to 90% of its peak-to-peak voltage. But the percentage can be changed arbitrarily

FALL TIME

Similarly, the time for the signal to go from 90% to 10% of its peak-to-peak voltage.



The rise and fall times depend on factors such as:

- how much of the light is absorbed at a specific wavelength,
- -the width of the intrinsic region,
- Various photodiode and electronics capacitance values, and
- various detector and electronic resistances.

As a result, the rise and fall times are not necessarily equal in a receiver. **For example**, large capacitance values can cause a long decay tail to appear in the falling edge of the output pulse, thereby creating long fall times.

Bandwidth

The response speeds of the photodiode and the electronic components result in a gradual drop in the output level beyond a certain frequency. The point at which the output has dropped to 50 percent of its low-frequency value is called the *3-dB point*. At this point only one-half as much signal power is getting through the detector compared to lower frequencies.

The 3-dB point defines the receiver *bandwidth* (sometimes referred to as the *3-dB bandwidth*), which is the range of frequencies that a receiver can reproduce in a signal.

If the rise and fall times are equal, the 3-dB bandwidth (in megahertz) can be estimated from the rise time by the relationship

$$\text{Bandwidth, MHz} = \frac{350}{\text{rise time, ns}} \qquad \text{[nm]}$$

Other characteristics

- Dynamic range-optical input power they can receive (to keep BER<10^-9 or -12)

- If the maximum optical input power was –14 dBm and the minimum optical input power was –32 dBm, the dynamic range would be 18 dB.

- Operating wavelength-A receiver designed for1300 nm may not perform well or not perform at all when connected to an 850 nm or 1550 nm transmitter.

Operating characteristics

Parameter	Symbol	Min.	Typ.	Max.	Unit
Ambient operating temperature	T_A	0		70	°C
Supply voltage	V_{CC}	4.75		5.25	V
Data input voltage—low	$V_{IL} - V_{CC}$	−1.810		−1.475	V

Parameter	Symbol	Min.	Typ.	Max.	Unit
Data input voltage—high	$V_{IH} - V_{CC}$	−1.165		−0.880	V
Data and signal detect output load	R_L		50		Ω

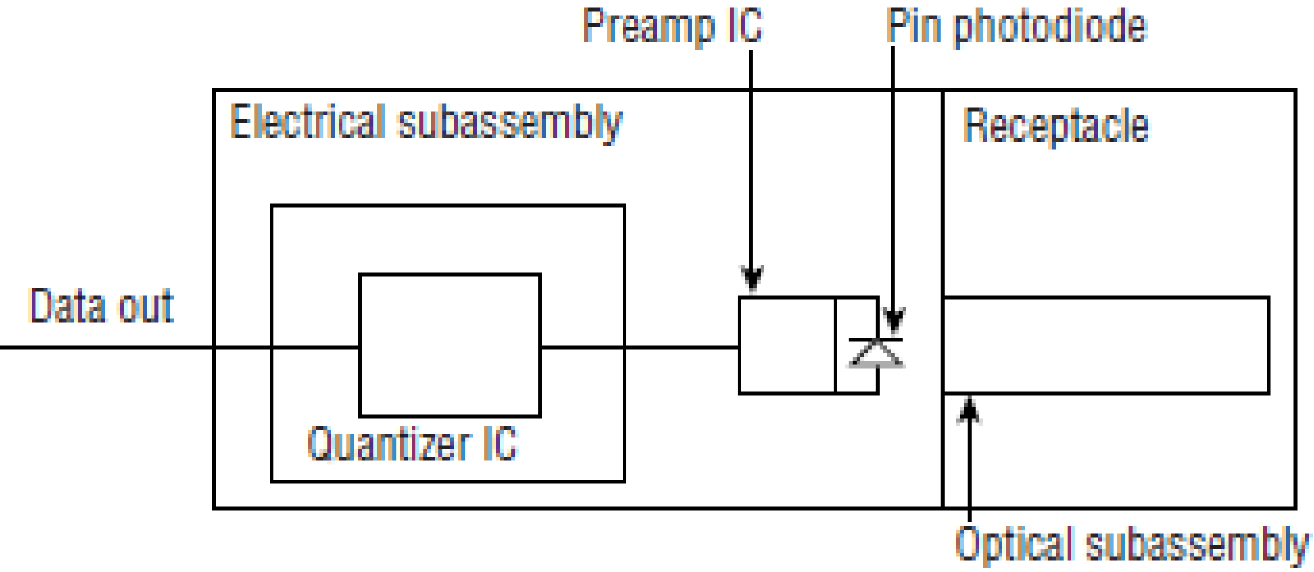
Electrical characteristics

Parameter	Symbol	Min.	Typ.	Max.	Unit
Supply current	I_{CC}		82	145	mA
Power dissipation	P_{DISS}		0.3	0.5	W
Data output voltage—low	$V_{OL} - V_{CC}$	−1.840		−1.620	V
Data output voltage—high	$V_{OH} - V_{CC}$	−1.045		−0.880	V
Data output rise time	t_r	0.35		2.2	ns
Data output fall time	t_f	0.35		2.2	ns
Signal detect output voltage—low	$V_{OL} - V_{CC}$	−1.840		−1.620	V
Signal detect output voltage—high	$V_{OH} - V_{CC}$	−1.045		−0.880	V
Signal detect output rise time	t_r	0.35		2.2	ns
Signal detect output fall time	t_f	0.35		2.2	ns

Fiber optic receivers and performance measurements (SNR, OSNR, BER)

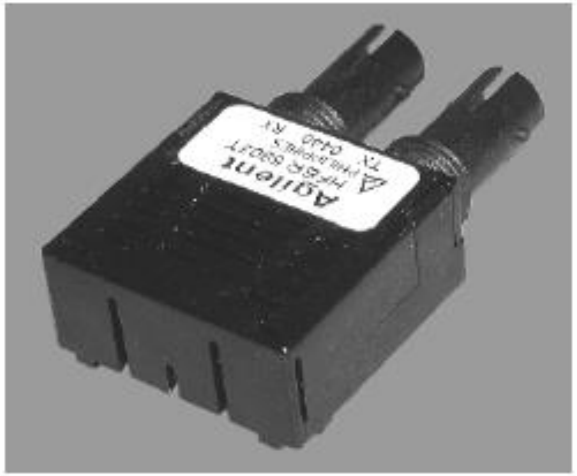
- The *optical receiver* is a combination of the
  - optical detector - modulated optical input conversion in electric signal
  - electronic preamplifier, and the
  - electronic processing elements that recover information sent on the optical signal.
- The design and implementation of the receiver portion of the system is most difficult, because the receiver could be working with the weakest optical signal and we do not want to contaminate the signal with noise.

Fiber Optic Receivers

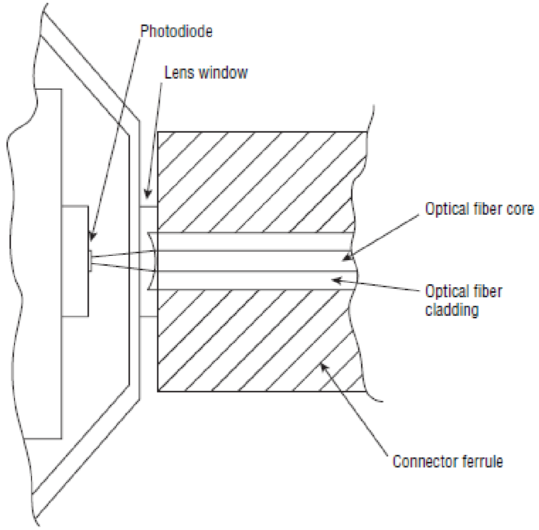


The *receptacle* is the part of the fiber optic receiver that accepts the connector. It also aligns the ferrule so that the optical fiber within the ferrule is perpendicular with the window edge in the optical assembly. Receiver or transceiver modules are manufactured to support a variety of connector types.

tranceiver



Optical connection

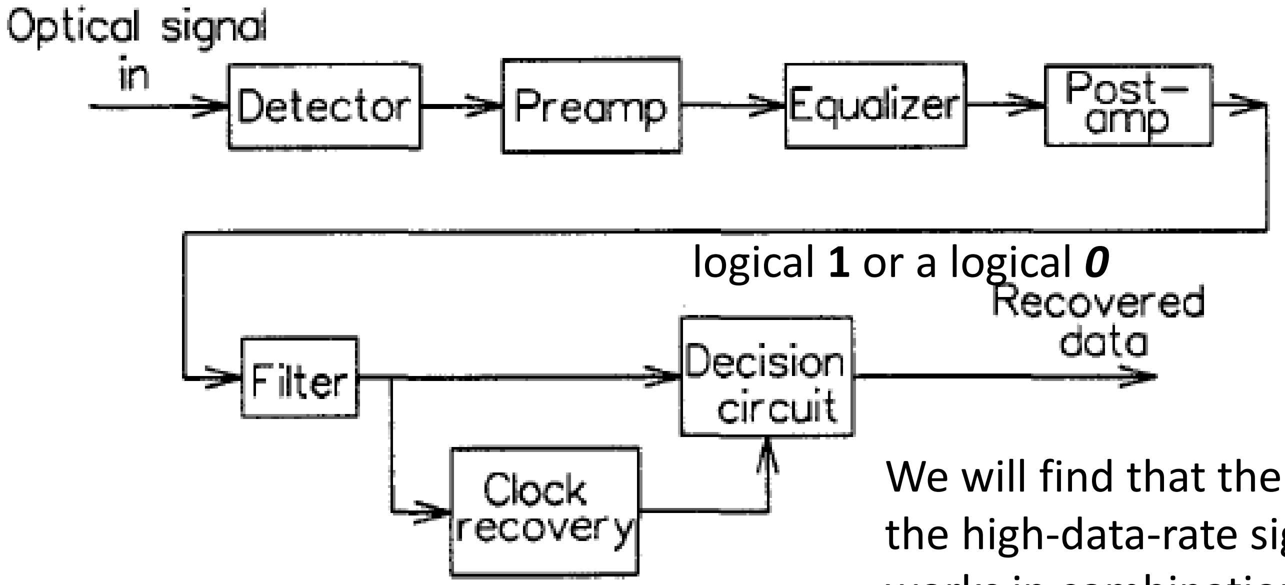


The photodiode converts the light pulses from the optical fiber to electrical current pulses, as discussed earlier. The *transimpedance amplifier*, or preamplifier, amplifies the electrical current pulses from the photodiode and outputs voltage pulses to the quantizer IC.

The *limiting amplifier* in the quantizer IC amplifies the voltage pulses and provides a binary decision. It determines whether the electrical pulses received represent a binary 1 or a binary 0.

Block diagram

The *optical detector* converts the modulated optical input into an electronic signal for further processing.



logical **1** or a logical ***0***

Because the optical signal is typically weak, the next step is to amplify the signal with the *preamp.* It is crucial to minimize the noise added by this amplifier.

We will find that the lowest-noise preamplifiers lack the bandwidth to handle the high-data-rate signals used in fiber communications; therefore, the *equalizer* works in combination with the preamp to restore the required bandwidth. The equalizer can also be used to help alleviate the problems caused by data spilling out into adjacent bit periods because of pulse spreading. Following the equalizer, the signal is boosted further with the *postamplifier,* frequently with some sort of automatic gain control that adjusts the gain subject to the strength of the signal.

The *filter* following the postamp removes unwanted frequency components that might have been generated by the signal processing to this point.

Photodetector noise

The most meaningful criterion for measuring the performance of a digital communication system is the *average error probability*. In an analog system the fidelity criterion usually is specified in terms of a peak *signal-to-noise ratio*.

The calculation of the error probability for a digital optical communication receiver differs from that of its electronic counterpart. This is a result of the discrete quantum nature of the optical signal and also because of the probabilistic character of the gain process when an avalanche photodiode is used.

The *signal-to-noise ratio* SNR (also designated by S/N) at the output optical receiver is defined by

$$\text{SNR} = \frac{\text{signal power from photocurrent}}{\text{photodetector noise power} + \text{amplifier noise power}}$$

The term *noise* describes unwanted components of a signal that tend to disturb the transmission and processing of the signal in a physical system. Noise is present in every communication system and represents a basic limitation

The noises in the receiver arise from the statistical nature of the randomness of photon-to-electron conversion process and the electronic noise in the receiver amplification circuitry

SNR

To achieve a high SNR, the numerator in Equation should be maximized and the denominator should be minimized. Thus, the following conditions should be met:

1. The photodetector must have a high quantum efficiency to generate a large signal power.

2. The photodetector and amplifier noises should be kept as low as possible.

3. Typical error rates specified for optical fiber telecommunication systems range from 10^-9 to 10^-15. The BER also is known as the *error probability*, which commonly is abbreviated as *Pe*.

The *signal-to-noise ratio* SNR (also designated by S/N) at the output optical receiver is defined by

$$\text{SNR} = \frac{\text{signal power from photocurrent}}{\text{photodetector noise power} + \text{amplifier noise power}}$$

Sources of noise

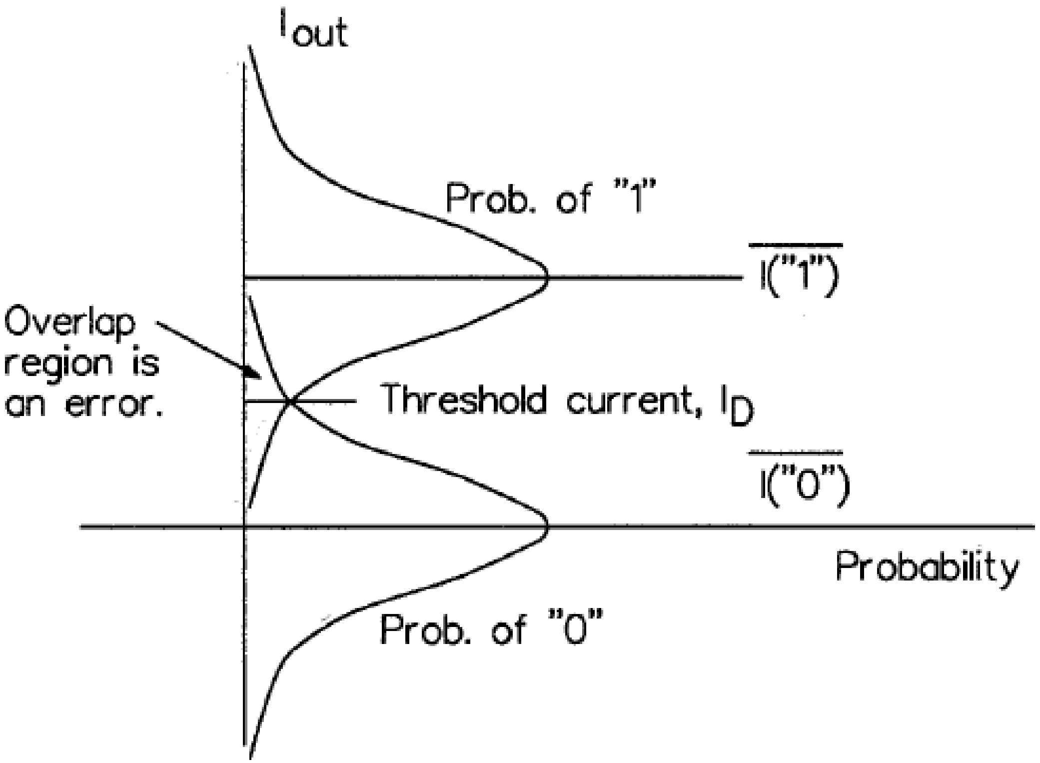
The total probability of making an error is the sum of the probability of calling a **1** a **0** (given that a **1** was sent), plus the probability of calling a **0** a **1** (given that a **0** was sent). Mathematically, this is written as

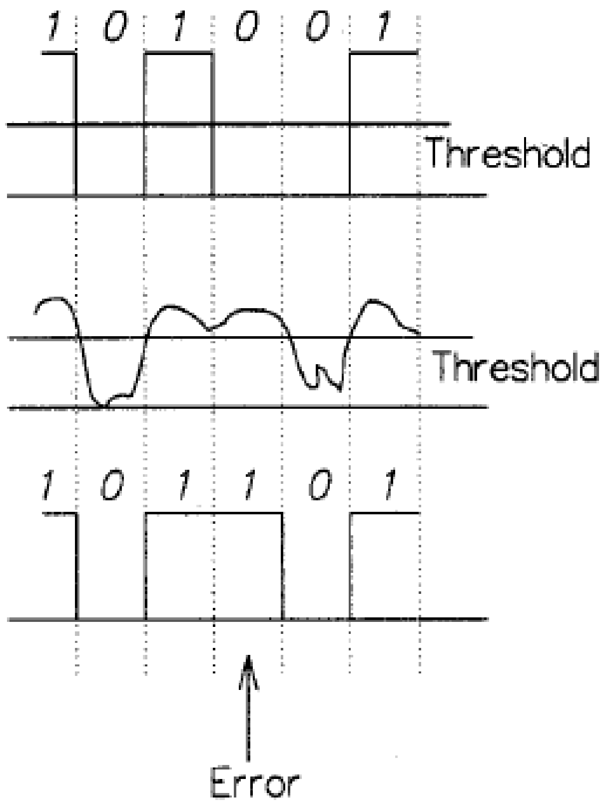
$$P_e = P(0|1)P(1) + P(1|0)P(0)\,, \tag{6.71}$$

- quantum or shot noise - arises from the statistical nature of the production and collection of photoelectrons. It has been found that these statistics follow a Poisson process and
- dark current associated with photodetection - arises from electrons and holes that are thermally generated at the *pn* junction of the photodiode. This current continues to flow through the bias circuit of the device when no light is incident on the photodetector. In an APD these liberated carriers also get accelerated by the electric field across the device and therefore are multiplied by the avalanche mechanism.

  and
- thermal noise occurring in the electronics - arises from the random motion of electrons that is always present at any finite temperature.

Density probability functions





Eye diagram interpretation and BER

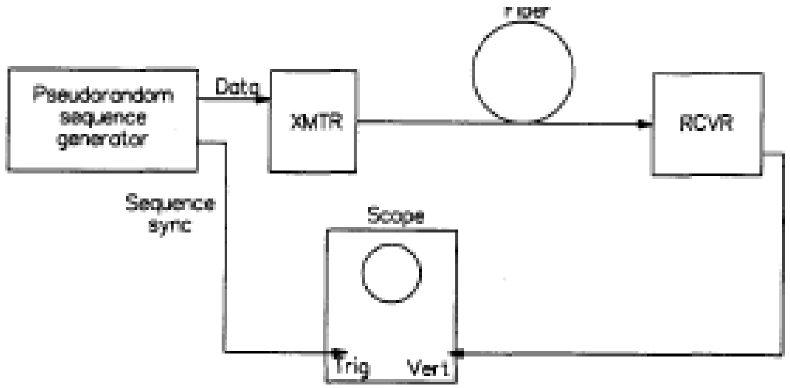


Figure 6.21 Experimental setup for observing the eye pattern of a fiber optic digital link.

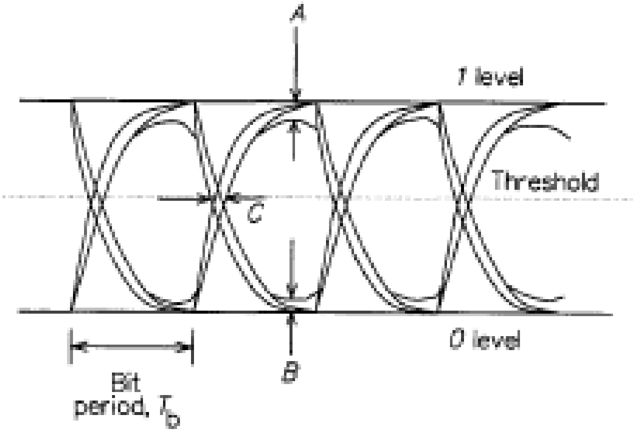


Figure 6.22 Representative eye pattern.

The horizontal width of the eye opening gives the optimum *sampling time interval* for the received signal to be sampled without error from intersymbol interference. The optimum sampling time is at the position of maximum eye opening. *intersymbol interference*)

The vertical height of the eye opening is a measure of the *amplitude distortion* of the signal. As the upper limit of the frequency response of the system is reached, the vertical height of the eye opening will decrease and the eye will close.

- The spacing of "A" on the figure indicates the amount of noise present when a logical **1** is sent; the spacing of "B" on the figure indicates the amount of noise present when a logical **0** is sent.
- The width of the threshold crossing ("C" on the figure) determines the *timing/jitter* (or

Eye patterns are also useful to identify the *performance penalty* associated with the introduction of a change to the link. The eye patterns with and without the desired changes are measured and compared. The ratio of the **1**-level voltage to the **0**-level voltage is expressed in dB. The difference in the dB values is the performance penalty associated with the change.

BER~ $\dfrac{1}{\sqrt{2\pi}}\dfrac{e^{-Q^2/2}}{Q}$ Where Q=SNR

$Q = 6$ for BER $= 10^{-9}$, $Q = 7$ for BER $= 10^{-12}$, and Q $= 8$ for BER $= 10^{-15}$.

Eye diagram – cap 14

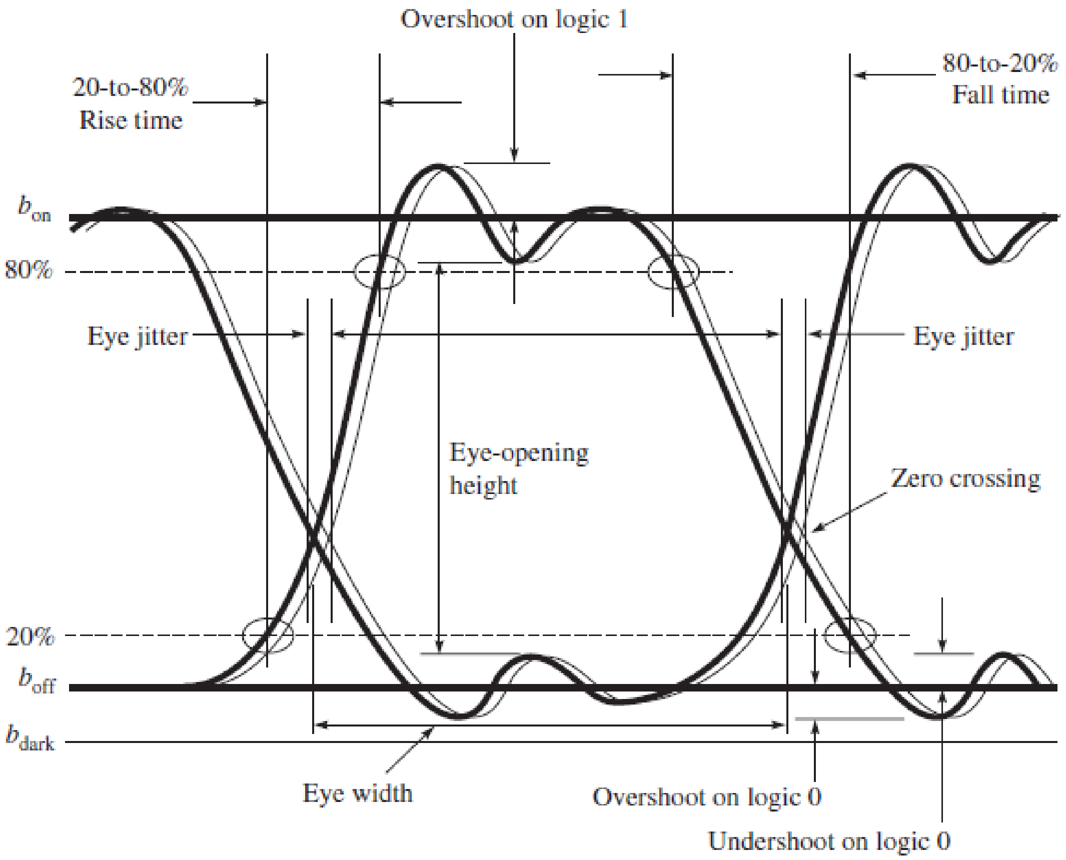


Figure 14.2. General configuration of an eye diagram showing definitions of fundamental measurement parameters.

Timing jitter (also referred to as *eye jitter* or *phase distortion*) in an optical fiber system arises from noise in the receiver and pulse distortion in the optical fiber. If the signal is sampled in the middle of the time interval (i.e., midway between the times when the signal crosses the threshold level), then the amount of distortion ΔT at the threshold level indicates the amount of jitter. Timing jitter is thus given by

$$\text{Timing jitter (percent)} = \frac{\Delta T}{T_b} \times 100 \text{ percent} \qquad (14.4)$$

where T_b is the bit interval.

OSNR

The resultant information of signal power versus wavelength is useful for determining the optical signal-to-noise ratio (OSNR), finding the absolute wavelength of a specific channel,
and verifying that the channel spacing is adhering to the ITU wavelength specification.

A major challenge in the operation of WDM networks is how to verify that thesystem is functioning properly. Thus there is a crucial need to monitor each wavelength intelligently in order to meet network reliability requirements and to guarantee a specific *quality of service* (QoS) to the end customer, as spelled out in a *service-level agreement* (SLA). The key performance parameters to monitor are wavelength, optical power, and optical signal-to-noise ratio (OSNR).

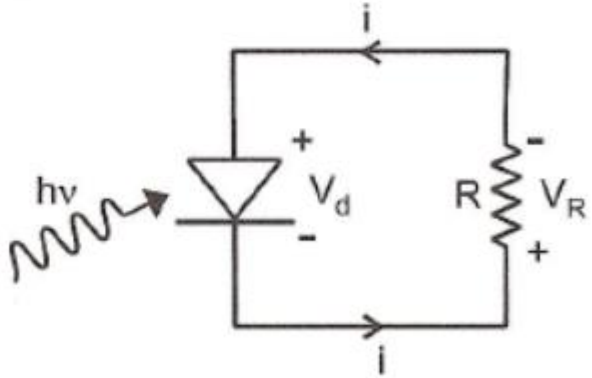
Typical values

Characteristic	pin diodes			APDs	
	Silicon	Germanium	InGaAs	Silicon	Germanium
λ (μm)	0.4–1.1	0.5–1.8	1.0–1.5	0.4–1.1	0.5–1.65
Quantum efficiency	80%	50%	70%	80%	75%
Rise time (ns)	0.01	0.3	0.1	0.5	0.25
Bias voltage	15	6	10	170	40
Responsivity (A/W)	0.5	0.7	0.4	0.7	0.6
Gain	1	1	1	80-150	80-150

Application: Solar cell

- A solar cell is a ‘very large photodiode’ that operates in the photovoltaic mode and that converts optical power P_{in} into electrical power P_{elec}

$$P_{elec} = Ri^2 \text{ and } \begin{cases} V_d = -Ri \\ i = i_0\left[e^{\frac{eV_d}{\beta k_B T}} - 1\right] - i_\lambda \end{cases}$$



- Consider sufficient optical power P_{in}

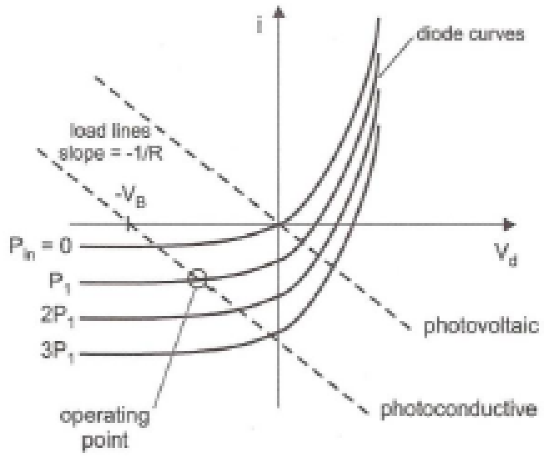
➔ $i_\lambda \gg i_0 \Rightarrow i = i_0 e^{\frac{-eiR}{\beta k_B T}} - i_\lambda$

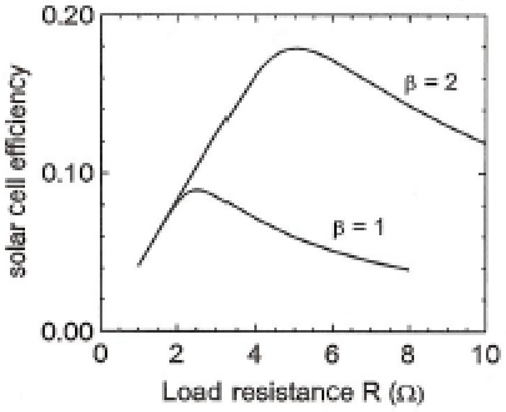
- Solar cell efficiency

$$\eta_{SC} \triangleq \frac{P_{elec}}{P_{in}} = \frac{Ri^2}{P_{in}}$$

Application: Solar cell

- The load R can be chosen to optimize the efficiency η_{SC}
  - Adapt R such that slope $-1/R$ is such that load line intersects diode curve where $|iV_d|$ is maximum
- Typical efficiencies
  - Monocrystalline Si – 25%
  - Polycrystalline Si – 20%
  - Amorphous Si – 10%
  - Multijunction heterogeneous – 40%





Real world scenario

Not too long ago, a coworker and Jim were troubleshooting a communication problem between a piece rack–mounted computing equipment and a router. The equipment and the router were communicating over 50/125 ⌠m multimode optical fiber. Everything would work for a while, and then the equipment and router would stop communicating.

Typically, when things like this happen, the programmers blame the failure on the hardware and we hardware engineers blame the failure on the software. Because Jim and coworker had worked together on the design of the network switch in the computing equipment, they immediately became involved when the communication failure occurred. The next phase was troubleshooting to prove that the hardware was not the problem.

During the troubleshooting process, someone questioned whether the receiver on the router was receiving any light energy from the switch's transmitter. Because the two pieces of equipment communicate at a wavelength of 1550 nm, the light is not visible.

To quickly answer that question, a power meter was used to measure the optical output power from the transmitters

on both pieces of equipment. A mode filter was used on the 1-meter jumper from the transmitter to the power meter.

The measurements obtained were compared to the manufacturer's optical characteristics for both the transmitter and the receiver. The optical output power for each transmitter was within specifications. About the same time that we determined the hardware was functioning properly, the programmers made some minor changes and the problem was resolved.

Conclusions

Describe the basic operation of a photodiode. Be able to describe the basic operation of a photodiode. Remember that the job of the photodiode is to convert optical energy into electrical energy.
Describe the operation of a PIN photodiode. Be able to describe the basic operation of the PIN photodiode. Remember that the PIN photodiode works like a PN photodiode but offers better performance, with improved efficiency and greater speed.
Describe the operation of an avalanche photodiode (APD). Be able to describe the basic operation of an avalanche photodiode. Remember that a small bundle of photons can trigger an avalanche of electrons. The APD accomplishes this through a process called photomultiplication.
Describe the performance characteristics of commonly used photodiodes. Be able to describe the three performance characteristics of commonly used photodiodes. Remember that the three common characteristics are responsivity, quantum efficiency, and switching speed.
Describe the basic components in a fiber optic receiver. Be able to describe the three basic components of a fiber optic receiver. Remember that a receiver is typically made up of an electrical subassembly, optical subassembly, and receptacle.
Describe receiver performance characteristics. You should know that the performance characteristics of the receiver are typically broken up into four groups: recommended operating conditions, electrical characteristics ,optical characteristics, and data rate. Make sure you understand that recommended operating conditions describe the maximum and minimum temperature and voltage ranges that the device can operate in without damage. The electrical characteristics of the receiver describe the supply current requirements, the data output requirements, and the power dissipated by the device. The optical characteristics of the receiver at a minimum include minimum optical input power, maximum optical input power, and operating wavelength.