Light Detectors

- Light can be detected by the eye. The eye is not suitable for modern fiber communications because its response is too slow, its sensitivity to low-level signals is inadequate, and it is not easily connected to electronic receivers for amplification, decoding, or other signal processing.
- Furthermore, the spectral response of the eye is limited to wavelengths between 0.4 and 0.7, where fibers have high loss.
- Nonetheless, the eye is very useful when fibers are tested with visible light.
- Breaks and discontinuities can be observed by viewing the scattered light.
- Systems, such as couplers and connectors, can be visually aligned with the visible souses before the infrared emitter is attached.
- The remainder of this chapter is confined to an investigation of devices that directly convert optic radiation to electrical signals (either current or voltage) and that respond quickly to changes in the optic power level.

7-1 PRINCIPLES OF PHOTODETECTION

- We will look at **two** distinct photodetection mechanisms.
- The **first** is the ***external photoelectric effect***, in which electrons are freed from the surface of a metal by the energy absorbed from an incident stream of photons.
    1. The vacuum photodiode and
    2. the photomultiplier tube are based on this effect.
- A **second** group of detectors are **semiconductor** junction devices in which free charge earners "(electrons and holes) are generated by absorption of in-coming photons. This mechanism is sometimes called the ***internal photoelectric effect***.
- Three **common devices** using this phenomenon are :
    1. the *pn* junction photodiode,
    2. the PIN photo-diode, and
    3. the avalanche photodiode.
- Important detector **properties** are :
    - responsivity,
    - spectral response, and
    - rise time.

Responsive

- The ***responsive*** *p* is the ratio of the output current of the detector to its optic input power. In equation form it is

$$\rho = \frac{i}{P} \qquad (7\text{-}1)$$

- The units of responsivity are **amperes per watt**.
- In some detector configurations the electrical output is a voltage.
- In this case, the responsivity is given in **units of volts per watt** of incident power.

Spectral response

- The ***spectral response*** refers to the curve of detector responsivity as a function of wavelength.
- Because of the rapid change in responsivity with wavelength, different detectors must be used in the **windows** of the optic spectrum where fiber losses are low.
- Within any of the windows, the responsivity at the specific wavelength emitted by the source must be used when designing the receiver.

Rise time

- The **rise time** t_r is the time for the detector output current to change from 10 to 90% of its final value when the optic input power variation is a step. It is same as optic sources.
- Detector rise time is illustrated in Fig, 7-1. The 3-dB modulation bandwidth of the detector is

$$f_{3\text{-dB}} = \frac{0.35}{t_r} \qquad (7\text{-}2)$$

- At this frequency the electrical signal power in the receiver is half of that obtained at very low modulation frequencies, assuming the same amount of optic signal power incident on the detector in both cases.

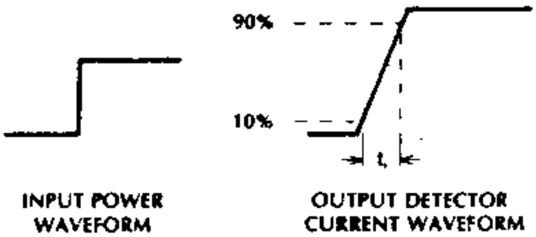


Figure 7-1 Photodetector rise time.

7-2 PHOTOMULTIPLIER

- The vacuum photodiode and photomultiplier tube **are not placed** in operational fiber systems, although useful in **testing** of fiber components.
- The high sensitivity of the photomultiplier makes it particularly helpful when **measuring low levels** of optic power.
- Photoemissive detectors are somewhat easier to explain than semiconductor devices, and the two have many properties in common.
- For this reason we will begin our discussion of photodetector operation with the photoemitters.
- A vacuum photodiode is sketched in Fig. 7-2.
- A bias voltage is applied, making the anode positive and the cathode negative.
- With **no light**, the current passing through the load resistor is zero and the **output voltage is zero**.
- When the cathode is irradiated with light, incoming photons are **absorbed**, giving up their **energies to electrons** in the metal.
- Some of these electrons gain enough energy to **escape from the cathode**.
- These free electrons **move toward the anode**, attracted by its positive charge.
- During this movement, positive charge is drawn through the external circuit (i.e., through the load resistor) to the anode, attracted by the approaching negatively charged electrons.
- In other words, current flows through the circuit. When the electrons strike the anode, they combine with the positive charges and the circuit current stops.
- To liberate a single electron from the cathode requires a minimum amount of energy, called the ***work function**.* An incoming photon must possess at least this much energy to cause electron emission.

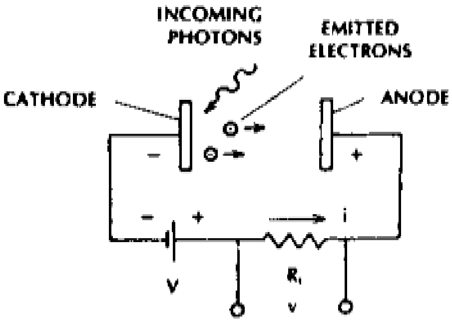


Figure 7-2 Vacuum photodiode.

Photomultiplier tube (PMT)

- The photomultiplier tube (PMT) has much greater responsivity than does the photo-diode because of an **internal gain** mechanism.
- A PMT is represented schematically in Fig. 7-3. Electrons emitted from the cathode are accelerated toward an electrode called a **dy*node***.

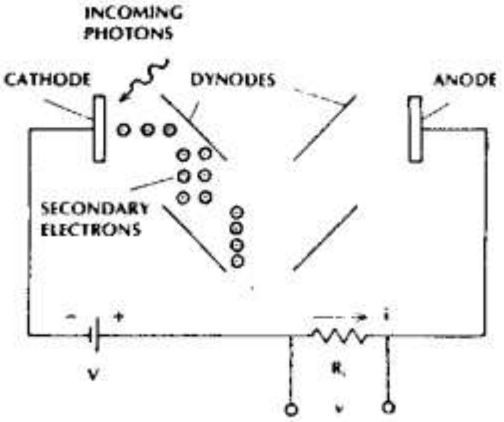


Figure 7-3 Photomultiplier

- The first dynode attracts electrons because it is placed at a higher voltage than the cathode, typically 100 V or more.
- The electrons hitting the dynode have high kinetic energies. They give up this energy, causing the release of electrons from the dynode.
- This process is called ***secondary emission***. An incident electron can liberate more than one secondary electron, thus **amplifying** the detected current.
- The current is amplified at each of the successive dynodes. Each dynode must be at a **higher** voltage than the preceding one in order to attract (and thus accelerate) the electrons.
- Amplification within a detector, such as occurs in the PMT, is ***internal* gain**.
- This is in contrast to *external* gain, which can be obtained from electronic amplifiers following the detector.
- Internal gain has an important **advantage**. It increases the signal level without significantly lowering the ratio of **signal power-to-noise power**.
- External amplifiers always add noise, diminishing the signal-to-noise ratio.
- Because of their high gain, photomultipliers are useful in detecting low levels of radiation and in overcoming noise originating from thermal sources.
- Photomultipliers are very fast. Some have rise times of a few tenths of a nanosecond.
- Their **disadvantages** include high cost, large size, high weight, and the need for a power supply providing hundreds of volts for bias.

7-3 SEMICONDUCTOR PHOTODIODE

- Semiconductor junction photodiodes are small, light, sensitive, fast, and can operate with just a few bias volts. They are almost **ideal** for fiber systems. We will investigate three forms of these devices:
    - The pn photodiode,
    - PIN detector
    - avalanche photodiodes.

- The **simple *pn* photodiode**, drawn in Fig. 7-4, illustrates the basic detection mechanism of a junction detector.
- When *reverse* biased, the potential energy barrier between the *p* and *n* regions increases.
- Free electrons (which normally reside in the *n* region) and free holes (normally in the *p* region) cannot climb the barrier, so no current flows.
- The *junction* refers to the region where the barrier exists.

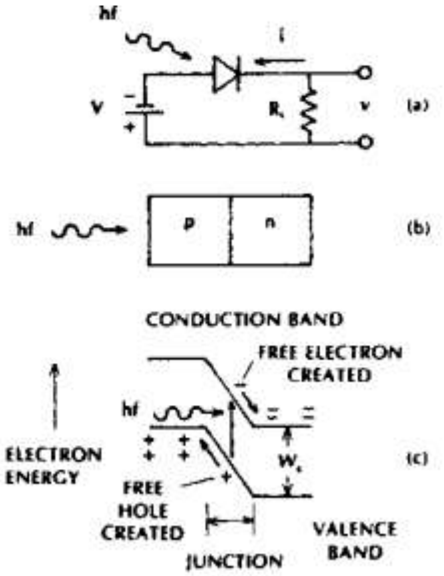


Figure 7-4 Semiconductor junction photodiode. (a) Reverse-biased diode. (b) *pn* junction. (c) Energy-level diagram.

- Because there are no free charges in the junction, it is called the ***depletion region.***
- Having no free charges, its resistance is high, resulting in almost all the voltage drop across the diode appearing across the junction itself.
- Therefore, the electrical forces are high in the depiction region and negligible outside.

- Figure 7-4(c) shows an incident photon being absorbed in the junction after passing through the *p* layer.
- The absorbed energy raises a bound electron across the bandgap from the valence to the conduction band. The electron is now free to move.
- A free hole is left in the valence band at the position vacated by the electron. Free charge carriers are created by photon absorption in this manner.
- The electron will travel down the barrier, and the hole (whose potential energy is opposite that of an electron) will travel up the barrier.
- These moving charges cause current flow through the external circuit in the same way that photoemitted electrons cause current in a vacuum photodiode.
- When the free holes and electrons recombine or when they reach the edge of the junction, where the electrical forces are small, the charges cease to move, which stops the current.

- **What happens when a photon is absorbed in the p or *n* regions, outside the junction?**
- An electron-hole pair is created, but these free charges will not move quickly because of the weak electrical forces outside of the junction.
- Most of the free charges will diffuse slowly through the diode and recombine before reaching the junction.
- These charges produce negligible current, thus reducing the detector's responsivity.
- Clearly, this phenomenon makes the *pn* detector inefficient. To increase the response, a **preamplifier** may be integrated onto the same chip as the diode. The resulting device is an ***integrated detector preamplifier (IDP).***

- It is interesting to **compare** the semiconductor junction used as a light emitter and as a light detector.
- For **emission**, the diode is forward biased, and charges injected into the junction recombine to produce photons.
- For **detection**, the process is reversed: the diode is reverse biased and incoming photons generate electron-hole pairs, producing electrical current. Although not commonly done, a single *pn* device could be designed to be used as both an emitter and a detector.

7-4 PIN PHOTODTODE

- PIN photodiodes are the most common detectors in fiber systems.
- PIN diode has a wide ***intrinsic*** semiconductor layer between the *p* and n regions, as illustrated in Fig. 7-5.

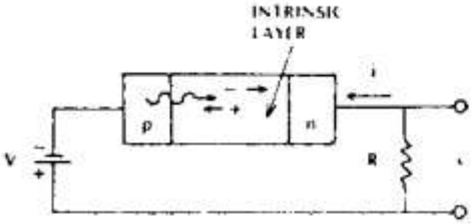


Figure 7-5 PIN photodiode

- The intrinsic layer has **no free charges**, so its **resistance is high**, most of the diode voltage appears across it, and the electrical forces are strong within it.
- Because the intrinsic layer is so **wide**, there is a high probability that incoming photons will be absorbed in it rather than in the **thin *p* or *n*** regions. This improves the efficiency and the speed relative to the *pn* photodiode.

Cutoff Wavelength

- To create an electron-hole pair, an incoming photon must have enough energy to raise an electron across the bandgap.
- This requirement, $hf >= W_g$, leads to a cutoff wavelength

$$\lambda = \frac{1.24}{W_g} \qquad (7\text{-}11)$$

where λ is in µm and W_g is the bandgap energy in electron volts. This is just like Eq. (7-4) for photo-emitters.

Materials

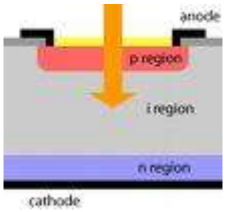
- Silicon is the most practical fiber optic detector in the **first window**, but Example 7-6 showed that it cannot be used in the long-wavelength second window around 1.3 µm.
- Germanium and InGaAs diodes introduce more noise than silicon, but they are responsive in the **second window**.
- Table 7-1 summarizes the useful ranges of the most common PIN diode materials.

TABLE 7-1. Semiconductor PIN Photodiodes

Material	Wavelength Range (µm)	Wavelength of Peak Response (µm)	Peak Responsivity (A/W)
Silicon	**0.3- 1.1**	**0.8**	**0.5**
Germanium	**0.5- 1.8**	**1.55**	**0.7**
InGaAs	**1.0-1.7**	**1.7**	**1.1**

Speed of Response

- The speed of response is limited by the ***transit time***, the time it takes for free charges to traverse the depletion layer.
- In a PIN diode, the length of the depletion region is just the width of the intrinsic layer.
- The velocity of the free charge carriers is linearly proportional to the magnitude of the reverse voltage, so higher voltages reduce the transit time.
- Capacitance also limits the response. Photodiodes designed for high-speed applications have capacitances of a few pico-farads or less.
- To obtain low capacitance, the diode's surface area must be small. For **efficient coupling**, however, the area cannot be reduced below that of the attached optic fiber's core.
- The speed of response may be limited by transit time or by the circuit rise time, whichever is larger.
- Rise times limited by transit time range from about 0.5 to 10 ns for fast PIN diodes. Rise times less than 100 ps have been achieved.



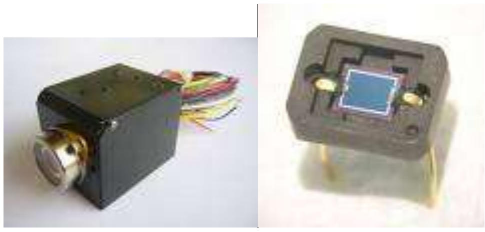
Packaging

- Photodetector packages are similar to those used for LEDs and laser diodes, but the requirements are less critical.
- The detector's active area is often larger than the core of the incoming fiber, so some lateral misalignment is tolerable.
- Also, detectors are not restricted by a low numerical aperture.
- They accept light over a wide angular range.
- Angular misalignment and mismatch between the NA of the fiber and detector are not severe problems.

Photodiodes are packaged in numerous ways. A few of them follow:

1. The photodiode is mounted on a standard transistor header, much like the LED in Fig, 6-12. A clear glass cover, or a lens, is attached to the metal cap. A lens, if present, will focus light onto the detector active area. The lens collect light from a fiber that I larger than he detector, improving the detection efficiency. In some designs the cap is removable to provide ace to the diode.
2. The photodiode packages may include a fiber **pigtail** either with or without a connector on the output.
3. Photodiodes are placed inside dual inline packages DIP for mounting on PCBs.

An integrated preamplifier is included in some PIN detector packages.This is the IDP structure.



7-5 AVALANCHE PHOTODIODE

- The APD is a semiconductor junction detector that has internal gain, which increase its responsivity over pn or PIN devices.
- Having gain, the APD is similar to the photomultiplier tube. The avalanche gain is however much lower than available from a PMT, being limited to values of several hundred or less.
- Such gain make APD much more sensitive than PIN diodes.
- Internal gain yields much better signal-to-noise ratios than can be obtained with external amplification.
- **Avalanche current multiplication comes about following**:
  - A photon is absorbed in the depletion region, creating a free electron and a free hole.
  - The large electrical forces in the depletion region cause these charges to accelerate, gaining kinetic energy.
  - When fast charges collide with neutral atoms, they create **additional electron-hole pairs** by using part of their kinetic energy to raise electrons across the energy bandgap.
  - One accelerating charges can generate **several new secondary charges**. The secondary charges themselves, can accelerate and create even more electron-hole pairs. This is the process of avalanche multiplication.

Typical avalanche photodiode range from 20 to 80 A/W.

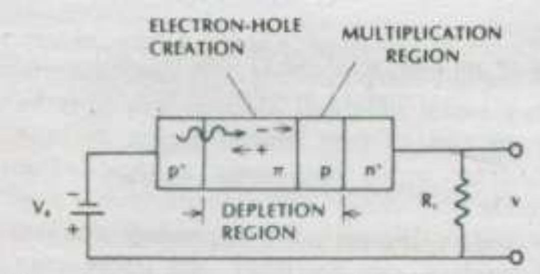


Figure 7-13 Reach-through avalanche photodiode.

- As with, the nonmultiplier PIN diode, the response speed of the APD is limited by the charge-carrier transit time and the *RC* time constant.
- Transit-time-limited avalanche photodiodes are available with rise times as low as a **few tenths of a nanosecond**. Rise times less than 100 ps have been achieved with both silicon and germanium.

- Avalanche photodiodes have excellent **linearity** over optic power levels ranging from a fraction of a nano-watt to several microwatts.
- If more than a microwatt is available at the receiver, an APD is usually not needed. At this power level PIN diodes provide enough responsivity and sufficiently large signal-to-noise ratios for most applications.
- The gain of an avalanche photodiode is temperature dependent, generally decreasing as the temperature rises.
- This occurs because the mean free path between collisions is smaller at higher temperatures.
- Many of the charge carriers do not get a chance to reach the high velocities required to produce secondary carriers.
- Temperature stabilization, or compensation, may be required in an APD receiver operating over an extended temperature range

TABLE 7- Typical Characteristics of junction Photo-detectors

Material	Structure	Rise Time (ns)	Wavelength (nm)	Responsivity (A/W)	Dark Current (nA)	Gain
Silicon	PIN	0.5	300-1100	0.5	1	1
Germanium	PIN	0.1	500-1800	0.7	200	1
InGaAs	PIN	0.3	900-1700	0.6	10	1
Silicon	APD	0.5	400-1000	75	15	150
Germanium	APD	1	1000-1600	35	700	50
InGaAs	APD	0.25	1000-1700	12	100	20

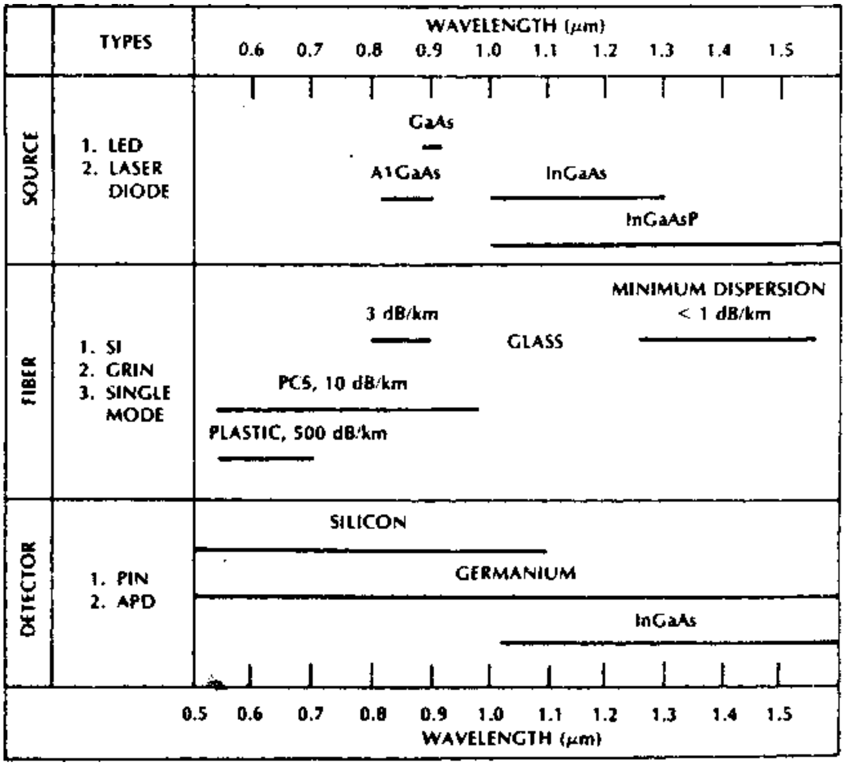


Figure 7-14 Major components of a fiber optic system.