9

Optical Detectors

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9.1. INTRODUCTION

A transducer is a device that converts input energy of one form into output energy of another form. An optical detector is a transducer that converts an optical signal into an electrical signal. This is done by generating an electrical current proportional to the intensity of incident optical radiation. The relationship between the input optical radiation and the output electrical current is given by the **detector responsivity.**

The predominant types of light detector used in communications systems relay on the principle of ionization in a semiconductor material. There are a number of different kinds of devices but they can all be viewed as variations on a central principle rather than as devices that involve radically different principles.

Photoconductors are semiconductors devices that can convert optical signals into electrical signals. Basically there are three processes for a general photoconductors :

(*i*) Generation of carrier by incident light.

(*ii*) Carrier transport and/or multiplication by whatever current gain mechanism may be present.

(*iii*) Interaction of current with external circuitry to provide the output signal.

9.2. REQUIREMENTS FOR OPTICAL DETECTORS

Fiber optic communication systems require that optical detectors should meet with the specific performance and compatibility requirements. Many of the requirements are similar to those of an optical source. The following criteria define the important performance and compatibility requirements for detectors :

DO YOU KNOW

A photodetector converts light energy into electrical energy which is the reverse energy conversion to a laser.

(*i*) **Small size :** Be compatible in size to low-loss optical fibers to allow for efficient coupling and easy packaging.

(*ii*) **Have a high sensitivity at the operating wavelength of the optical source :** The first generation systems have wavelength between 0.8 and 0.9 μm. However considerable advantage may be gained at the detector from the second generation sources with operating wavelegnth above 1.1 μm as both fiber attenuation and dispersion are reduced.

(*iii*) **Have a sufficiently short response time (sufficiently wide bandwidth) to handle the system's data rate :** Present systems extend into the hundreds of megahertz. However it seems that future systems will operate in GHz range and possible above.

(*iv*) Contribute low amounts of noise to the system.

(*v*) Maintain stable operation in changing environmental conditions, such as temperature.

(*vi*) It must be of low cost.

(*vii*) **Low bias voltage :** Ideally the detector should not require excessive bias voltages or currents.

(*viii*) **High reliability :** The detector must be capable of continuous stable operation at room temperature for many years.

(*ix*) **High fidelity :** To reproduce the received signal waveform with fidelity, for analogy transmission the response of the photodetector must be linear with regard to the optical signal over a wide range.

(*x*) **Large electrical response to the received output signal :** The photodetector should produce a maximum electrical signal for a given amount of optical power *i.e.,* the quantum efficiency should be high.

(*xi*) Dark current, leakage current and shunt conductance should be low.

Optical detector that meets many of these requirements and are suitable for fiber optic systems, are semiconductor photodiodes. The principal of optical detectors used in fiber optic systems include semiconductor positive-intrinsic-negative (PIN) photodiodes and avalanche photodiodes (APDs).

9.3. IMPORTANT PARAMETERS OF PHOTODETECTORS

When discussing photodetectors some important parameters are there :

(1) Detector Responsivity : Responsivity is the ratio of the optical detector's output photocurrent in amperes to the incident optical power in watts.

The responsivity of a detector is a function of the wavelength of the incident light and the efficiency of the device. For a particular material, only photons of certain wavelengths will generate a photocurrent when they are absorbed. Additionally, the detector material absorbs some wavelengths better than others. These two properties cause the wavelength dependence in the detector responsivity.

Responsivity is a useful parameter for characterizing detector performance because it relates the photocurrent generated to the incident optical power.

(2) Spectral Response Range : This is the range of wavelengths over which the device will operate.

(3) Response Time : This is a measure of how quickly the detector can respond to variations in the input light intensity. Response time can be affected by dark current, noise, linearity, back reflection and edge effect as shown in Fig. 9.1.

Edge effect results from the fact that detectors only provide fast response in their center region. The outer region of the detector has a higher responsivity than the center region, which can cause problems when aligning the fiber to the detector. The higher responsivity means the alignment of the fiber to the center region. Because response is much slower at the edge, this misalignment will reduce the response time of the detector.

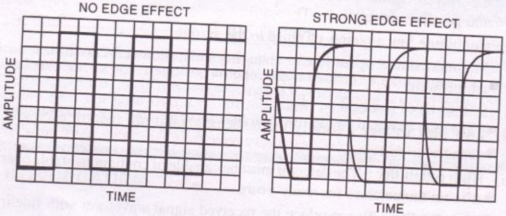

Fig. 9.1. Edge effect.

(4) Quantum Efficiency : It is defined by the ratio of primary electron-hole pairs created by incident photons to the photons incident on the detector material.

Detective quantum efficiency is given by :

$$\boxed{DQE = \left[\frac{\frac{S}{N_{out}}}{\frac{S}{N_{in}}}\right]} \quad ...(9.1)$$

So

$$\frac{S}{N_{out}} = \frac{S}{N_{in}} * DQE^{1/2}$$

Poisson statistics, $\boxed{\frac{S}{N_{in}} = N^{1/2}}$ ...(9.2)

(5) Capacitance : It depends upon the active area of the device and the reverse voltage across the device. This relationship is illustrated in Fig. 9.2.

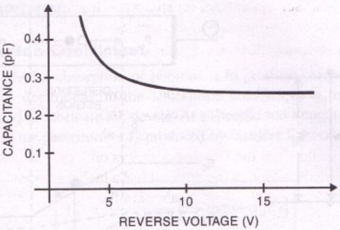

Fig. 9.2. C-V curve.

(6) Noise Characteristics : The level of noise produced in the device is critical to its operation at low levels of input light. There are several types of noise and these are :

- **Photon statistics limited noise** (photon arrival rate, by Poisson statistis, goes as qrt (n), n = number of photons).
- **Sky noise** caused by sky transparency changes and/or seeing/scintillation.
- **Johnson noise**-thermal agitation of electrons in detector (dark noise) reduced by cooling detector.
- **Readout noise.**
- **Electronics noise.**

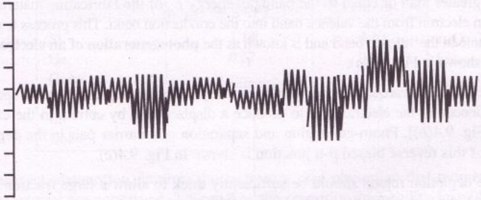

Fig. 9.3.

9.4. OPTICAL DETECTION PRINCIPLE

In an intrinsic absorber, the basic detection process is shown in Fig. 9.4, which illustrates a *p-n* photodiode.

Operation of the *p-n* photodiode :

(*a*) Photogeneration of an electron hole pair in an intrinsic semiconductor.

(*b*) Reverse bias *p-n* junction showing carrier drift in depletion region.

(*c*) Energy band diagram showing photo generation and separation of an electron hole pair.

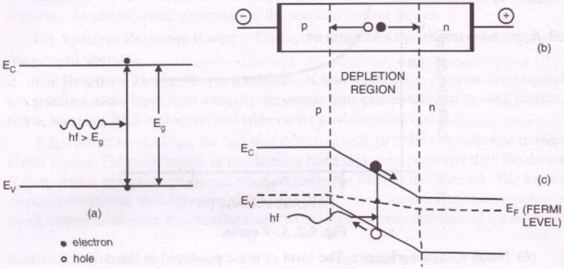

Fig. 9.4.

This device is reverse biased and because of developed electric field mobile carriers move to their respective majority sides. Therefore on either side of junction a depletion region or layer is created. This barrier stops the majority carriers to cross the junction in the opposite direction to the field. However, the field accelerates minority carriers from both sides to the opposite side of the junction, forming the reverse leakage current of the diode. Thus intrinsic conditions are created in the depletion region.

A photon incident in or near the depletion region of this device which has an energy greater than or equal to the bandgap energy E_g of the fabricating material, will excite an electron from the valence band into the conduction band. This process leaves an empty hole in the valence band and is known as the **photogeneration of an electron hole pair** as shown in Fig. 9.4(*a*).

Therefore, the carrier pairs generated near the junction are separated and swept under the influence of the electric field to produce a displacement by current in the external circuit[Fig. 9.4(*b*)]. Photo-generation and separation of a carrier pair in the depletion region of this reverse biased *p-n* junction is shown in Fig. 9.4(*c*).

The depletion region should be sufficiently thick to allow a large fraction of the incident light to be absorbed in order to achieve maximum carrier-pair generation. However, since long carrier drift times in the depletion region restrict the speed of operation of the photodiode, it is required to limit its width. Thus there is a trade off between the number of photons absorbed *i.e.*, sensitivity and the speed of response.

Types of Optical Detectors

The optical detectors are of three types :

(*i*) Photoemissive types (phototubes and photomultiplier tubes).

(*ii*) Photodiodes (*pn*-junction photodiodes, *p-i-n* photodiodes and avalanche photodiodes).

(*iii*) Photoconductors.

9.5. ABSORPTION

9.5.1. Absorption Coefficient

In a photodiode the absorption of photons is to produce carrier pairs and then a photocurrent. It is dependent on the absorption coefficient α_0 of the light in the semiconductor used to fabricate the device. At a specific wavelength and assuming only bandgap transitions the photocurrent I_P produced by incident light of optical power P_0 is given by

$$\boxed{I_P = \frac{P_0 e(1-r)}{hf}\left[1-\exp(-\alpha_0 d)\right]} \quad \text{...(9.3)}$$

where,
e = Charge on an electron
r = Fresnel reflection coefficient at semiconductor—air interface
d = Width of absorption region

The absorption coefficient of semiconductor materials are strongly dependent on wavelength.

9.5.2. Direct and Indirect Absorption : Silicon and Germanium

Silicon and germanium absorb light by both direct and indirect optical transitions. Table 9.1 indicates the bandgaps for some photodiode materials at 300 K.

Table 9.1. Direct and indirect bandgap values at 300 K.

	Bandgap (e_v) at 300 K	
	Indirect	**Direct**
Si	1.14	4.10
Ge	0.67	0.81
GaAs	—	1.43
InAs	—	0.35
InP	—	1.35
GaSb	—	0.73

Indirect absorption requires the assistance of a photon so that momentum as well as energy are conserved. This makes the transition probability less likely for indirect absorption than for direct absorption where no photon is involved. Silicon is weakly absorbing over the wavelength band of interest in optical fiber communication. This is because transitions over this wavelength band in silicon are due only to the indirect absorption mechanism. The bandgap for direct absorption in silicon is 4.10 eV, corresponding to a threshold of 0.30 μm in the ultraviolet, and thus is well outside the wavelength range of interest.

Another semiconductor material is germanium for which the lowest energy absorption takes place by indirect optical transitions. Threshold for direct absorption occurs at 1.53 μm, below which germanium becomes strongly absorbing. For germanium the indirect absorption will occur upto a threshold of 1.85 μm.

Ideally a photodiode material should be selected with a bandgap energy slightly less than the photon energy corresponding to the longest operating wavelength of the system. This provides a sufficiently high absorption coefficient to ensure a good response and yet limits the numbers of thermally generated carriers in order to achieve low dark current.

9.5.3. III-V Alloys

Germanium as a fabricating material for the semiconductor photodiodes has a drawback which lead to increased investigation of direct bandgap III-V alloys for the longer wavelength region. These materials are superior to germanium because their bandgap can be tailored to the desired wavelength by changing the relative concentrations of their constituents. They result in lower dark currents. They may also be fabricated in heterojunction structures which enhances their high speed operations.

Ternary allows such as InGaAs and GaAsSb deposited on InP and GaSb substrates respectively, have been used to fabricate photodiodes for the longer wavelength band. Quaternary alloys are also under investigation for detection at these wavelengths. Both InGaAsP grown on InP and GaAlAsSb grown on GaSb have been studied for this purpose.

9.6. QUANTUM EFFICIENCY

The quantum efficiency η is defined as the fraction of incident photons which are absorbed by the photodetector and generate electrons which are collected at the detector terminals.

$$\eta = \frac{\text{Number of electrons collected}}{\text{Number of incident photons}}$$

or

$$\boxed{\eta = \frac{r_e}{r_P}} \qquad ...(9.4)$$

where, r_e = Electron rate (electrons per sec.)

r_p = Incident photon rate (photons per second)

Absorption coefficient of the semiconductor material is an important factor which determines the quantum efficiency. Generally the quantum efficiency is less than unity because all of the incident photons are not absorbed to create electron hole pairs. In terms of absorption coefficient, the quantum efficiency is a function of the photon wavelength and must therefore only be quoted for a specific wavelength.

9.7. RESPONSIBILITY

The expression for quantum efficiency does not involve photon energy and therefore the responsivity R is often of more use when characterizing the performance of a photodiode. It is defined as

$$\boxed{R = \frac{I_P}{P_0}(AW^{-1})} \qquad ...(9.5)$$

where, I_P = Output photocurrent in amperes

P_0 = Incident optical power in watts

The responsivity gives the transfer characteristic of the detector (*i.e.*, photocurrent per unit incident optical power). Thus it is a useful parameter.

The relationship for responsivity

The energy of a photon is given by,

$$E = hf \qquad ...(9.6)$$

Thus the incident photon rate r_p in terms of incident optical power and the photon energy is given as

$$r_p = \frac{P_0}{hf} \qquad ...(9.7)$$

The electron rate is given by

$$r_e = \eta r_P = \eta . \frac{P_0}{hf} \qquad ...(9.8)$$

Therefore, the output photocurrent is

$$\boxed{I_P = \frac{\eta P_0 e}{hf}} \qquad ...(9.9)$$

where, e = Charge on an electron

Thus, the responsivity is written as

$$\boxed{R = \frac{\eta e}{hf}} \qquad ...(9.10)$$

The frequency f of the incident photons is related to their wavelength λ and the velocity of light in air c, by :

$$f = \frac{c}{\lambda}$$

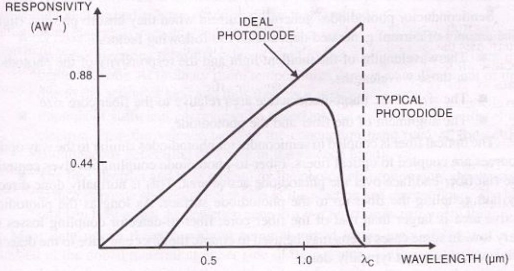

Fig. 9.5. Responsitivity against wavelength characteristic for an ideal silicon photodiode.

Substituting the value of f into Eq. (9.10), we get

$$\boxed{R = \frac{\eta e \lambda}{hc}} \quad ...(9.11)$$

The responsitivity is directly proportional to the quantum efficiency at a particular wavelength. Figure 9.5 shows the ideal responsivity against wavelength characteristic for a silicon photodiode with unit quantum efficiency. It also shows the typical responsivity of a practical silicon device.

9.8. LONG WAVELENGTH CUTOFF

In the intrinsic absorption process the energy of incident photons should be greater than or equal to the bandgap energy E_g of the material used to fabricate the photo detector. Thus, the photon energy

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

or

$$\boxed{\lambda \leq \frac{hc}{E_g}} \quad ...(9.12)$$

Therefore, the threshold for detection, commonly known as the **long wavelength cutoff point** λ_C is,

$$\boxed{\lambda_C = \frac{hc}{E_g}} \quad ...(9.13)$$

Above equation is applicable only to intrinsic photodetectors. Extrinsic photodetectors does not fulfill the above equation and it is not currently used in optical fiber communication.

9.9. PHOTODIODES

Semiconductor photodiodes generate a current when they absorb photons (light). The amount of current generated depends on the following factors :

- The wavelengths of the incident light and the responsivity of the photodiode at those wavelengths.
- The size of the photodiode active area relative to the fiber core size.
- The alignment of the fiber and the photodiode.

The optical fiber is coupled to semiconductor photodiodes similar to the way optical sources are coupled to optical fibers. Fiber-to-photodiode coupling involves centering the flat fiber-end face over the photodiode active area. This is normally done directly by butt coupling the fiber up to the photodiode surface. As long as the photodiode active area is larger than that of the fiber core, fiber-to-detector coupling losses are very low. In some cases a lens may be used to couple the fiber end-face to the detector. However, this is not typically done.

There are four different types of photodiodes :

(*i*) *p-n* photodiodes.

(*ii*) *p-i-n* photodiodes.

(*iii*) Avalanche photodiodes (APD).

(*iv*) Schottky barrier photodiode.

9.10. SEMICONDUCTOR PHOTODIODES WITHOUT INTERNAL GAIN

Semiconductors photodiodes without internal gain generate a single electron hole pair per absorbed photon.

9.10.1. P-N Photodiodes

Figure 9.6 shows a reverse biased *p-n* photodiode with both depletion and diffusion regions.

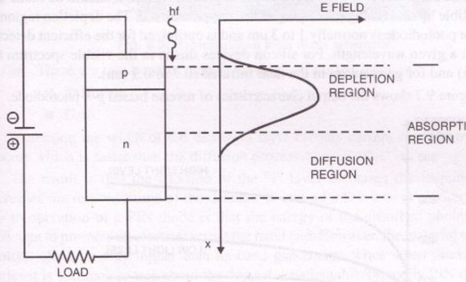

Fig. 9.6. ***p-n* photodiode showing depletion and diffusion regions.**

The principle involved in a *p-n* diode is simply the principle of the LED in reverse. That is light is absorbed at a *p-n* junction rather than emitted.

- A reverse biased *p-n* junction passes no current unless something happens to promote electrons from the valence band to the conduction band within the depletion zone. At ordinary room temperatures there is a small amount of this due to the action of heat and thus there is a very small current.
- Photons of sufficient energy can be absorbed and cause the promotion of an electron from the valence band to the conduction band (and of course the simultaneous generation of a hole in the valence band).
- The free electron and hole created by the photon absorption now are attracted to their opposite charges at either side of the junction and current flows. The big problem here is that the depletion zone in a *p-n* junction is extremely thin.

Most light passes through without being absorbed in the junction, instead it is absorbed in the doped material at either side of the junction. Ultimately many of the electron-hole pairs created outside the junction do end up being attracted to the junction and creating current. However the process is quite slow and *p-n* junction devices are not fast enough for current communications applications.

As shown in Fig. 9.6, photons may be absorbed in both the depletion and diffusion regions. The absorption regions position and width depends upon :

- the energy of the incident photons
- the material from which the photodiode is fabricated.

The absorption region may extend completely throughout the device in the case of the weak absorption of photons. Therefore the electron hole pairs are generated in both the depletion and diffusion regions.

In the depletion region the carrier pair separate and drift under the influence of the electric field, whereas in the outside region the hole diffuses towards the depletion region in order to be collected. The diffusion process is very slow as compared to drift and thus limits the response of the photodiode.

Since the photons are absorbed in the depletion region, it should be made as long as possible by decreasing the doping in the *n*-type material. The depletion region width in a *p-n* photodiode is normally 1 to 3 μm and is optimized for the efficient detection of light at a given wavelength. For silicon devices this is in the visible spectrum (0.4 to 0.7 μm) and for germanium in the near infrared (0.7 to 0.9 μm).

Figure 9.7 shows the output characteristics of reverse biased *p-n* photodiode.

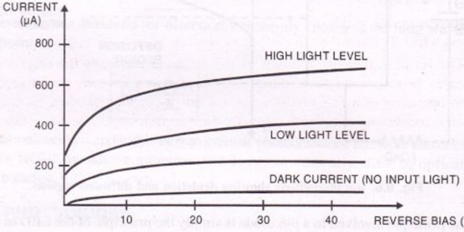

Fig. 9.7. Typical *p-n* photodiode output characteristics.

The different operating conditions are mentioned from no input light to a high light level.

9.10.2. *P-i-n* Photodiode

The problem created by the extreme thinness of a *p-n* junction is simplified by making it thicker. The junction is extended by the addition of a very lightly doped layer called the **intrinsic zone** between the *p* and *n* doped zones. Thus the device is called a *p-i-n* diode rather than a *p-n* diode. This is illustrated in Fig. 9.8.

The wide intrinsic (*i*) layer has only a very small amount of dopant and acts as a very wide depletion layer. There are a number of improvements here :

(*i*) It increases the chances of an entering photon being absorbed because the volume of absorbent material is significantly increased.

(*ii*) Because it makes the junction wider, it reduces the capacitance across the junction. The lower the capacitance of the junction the faster the device response.

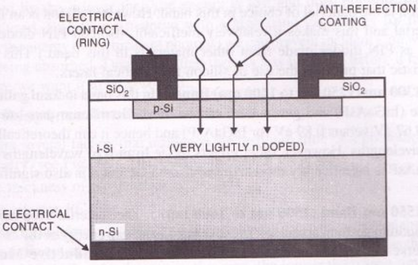

Fig. 9.8. Typical silicon *p-i-n* diode schematic.

(*iii*) There are two ways of current carriage across the junction :

- Diffusion
- Drift.

Increasing the width of the depletion layer favours current carriage by the drift process which is faster than the diffusion process.

The result is that the addition of the "*i*" layer increases the responsivity and decreases the response time of the detector to around a few tens of picoseconds. The key to operation of a PIN diode is that the energy of the absorbed photon must be sufficient to promote an electron across the band gap. However, the material will absorb photons of any energy higher than its band gap energy. Thus when discussing PIN diodes it is common to talk about the "cutoff wavelength". Typically PIN diodes will operate at any wavelength shorter than the cutoff wavelength. This suggests the idea of using a material with low band gap energy for all PIN diodes regardless of the wavelength.

Unfortunately, the lower the band gap energy the higher the "dark current" (thermal noise). Indeed but for this characteristic germanium would be the material of choice for all PIN diodes. It is low in cost and has two useful band gaps (an indirect band gap at 0.67 eV and a direct band gap at 0.81 eV). However it has a relatively high dark current compared to other materials.

This means that the materials used for PIN diode construction are different depending on the band of wavelengths for which it is to be used. However, this restriction is nowhere near as stringent as it is for lasers and LEDs where the characteristics of the material restrict the device to a very narrow range. The optimal way is to choose a material with a band gap energy slightly lower than the energy of the longest wavelength we want to detect.

9.10.2.1. Types of Materials Used

Typical materials used in the three communication wavelength "windows" are as follows :

(1) 500-1000 nm Band : Silicon PIN diodes operate over a range of 500 to 1120 nm as silicon has a band gap energy of 1.11 eV. Since silicon technology is very low cost, silicon is the material of choice in this band. However, silicon is an indirect band gap material and this makes it relatively inefficient. (Silicon PIN diodes are not as sensitive as PIN diodes made from other materials in this band.) This is the same characteristic that prevents the use of silicon for practical lasers.

(2) 1300 nm (1250 nm to 1400 nm) Band : In this band indium gallium arsenide phosphide (InGaAsP) and germanium can be used. Germanium has lower band gap energy (0.67 eV versus 0.89 eV for InGaAsP) and hence it can theoretically be used at longer wavelengths. However, other effects in Ge limit it to wavelengths below 1400 nm. InGaAsP is significantly more expensive than Ge but it is also significantly more efficient.

(3) 1550 nm Band (1500 nm to 1600 nm) : The material used here is usually InGaAs (indium gallium arsenide). InGaAs has a band gap energy of 0.77 eV. Operation with reverse bias as described above (called **"Photoconductive Mode") has a significant problem.** At low light levels the random current produced by ambient heat is a source of noise. At higher light levels however this is not a problem and the device offers the advantages of much higher speeds (than the alternative mode of operation) and linear response characteristics over a wide range.

The higher speed characteristics are the result of lowered capacitance caused by the widening of the depletion layer in the presence of reverse bias. If the device is operated without an externally applied current the natural potentials of the *p-i-n* junction will cause electrons and holes to migrate across the junction anyway. This is called "Photovoltaic Mode". Thus we get a small voltage (around 15 V) developed across the device.

The **advantage** of this is that there is much less "dark current" caused by ambient heat. Thus in this mode the device is more sensitive but the output requires immediate amplification because of the low voltage levels produced.

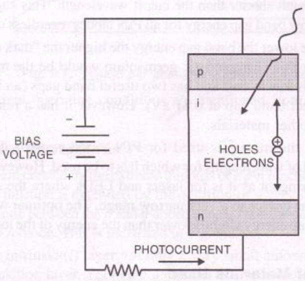

Fig. 9.9. A schematic representation of a photodiode.

The **efficiency** of *p-i-n* diodes at long wavelengths can be improved by the use of hetero-structures. For example using GaAlAs for the *p*-layer and GaAs for the *i* and *n*-layers. Incident light must pass through the *p*-layer before it enters the *i*-layer. If it is absorbed by the *p*-layer then the energy is lost and does not contribute to the current produced. By using a material with a high band gap energy for the *p*-layer (higher than the energy of the incident photons) we can prevent incident long wavelength light from being absorbed. This means that there is less light lost before it reaches the *i*-layer where we want it to be absorbed.

9.10.2.2. Response Time

There are several factors that influence the response time of a photodiode and its output circuitry (see Fig. 9.9). The most important of these are :

- the thickness of the detector active area
- the detector *RC* time constant.

The detector thickness is related to the amount of time required for the electrons generated to flow out of the detector active area. This time is referred to as the **electron transit time.** The thicker the detector active area, the longer the transit time will be.

The capacitance (*C*) of the photodiode and the resistance (*R*) of the load form the *RC* time constant. The capacitance of the photo detector must be kept small to prevent the *RC* time constant from limiting the response time. The photodiode capacitance consists mainly of the junction capacitance and any capacitance relating to packaging. The RC time constant is given by

$$\boxed{\tau_{RC} = RC} \qquad ...(9.14)$$

- Trade-offs between fast transit times and low capacitance are necessary for high-speed response. However, any change in photodiode parameters to optimize the transit time and capacitance can also affect responsivity, dark current, and coupling efficiency.
- A fast transit time requires a thin detector active area, while low capacitance and high responsivity require a thick active region.
- The diameter of the detector active area can also be minimized. This reduces the detector dark current and minimizes junction capacitance.
- However, a minimum limit on this active area exists to provide efficient fiber-to-detector coupling.

Linearity

Reverse-biased photodetectors are highly linear devices. Detector linearity means that the output electrical current (photocurrent) of the photodiode is linearly proportional to the input optical power.

Reverse-biased photodetectors remain linear over an extended range (6 decades or more) of photocurrent before saturation occurs. Output saturation occurs at input optical power levels typically greater than 1 milliwatt (mW). Because fiber optic communication systems operate at low optical power levels, detector saturation is generally not a problem.

9.10.2.3. Measures of Efficiency in p-i-n Diode

There are two common measures quoted when the efficiency of PIN photodetectors is discussed.

1. Quantum Efficiency : This is simply the ratio of the number of electrons collected at the junction over the number of incident photons. In an ideal situation 1 photon releases 1 electron (and its matching hole of course). A perfect quantum efficiency is therefore an efficiency of "1". In real devices QE is different at each operating wavelength and so it should always be quoted in association with a wavelength.

2. Responsivity : Quantum efficiency does not take account of the energy level of the incident photons.

Responsivity is a measure that does take photon energies into account. It is simply the output photocurrent of the device (in amperes) divided by the input optical power (in watts). Thus responsivity is quoted in amperes per watt. A typical value of responsivity for a silicon photodiode at a wavelength of 900 nm is 0.44.

Of course responsivity is very closely linked to quantum efficiency. It is just quantum efficiency adjusted to account for the variation in energy level implied by different wavelengths.

9.10.3. Speed of Response

There are three main factors which limit the speed of response of a photodiode. These are :

(*a*) **Drift time of carriers through the depletion region :** Fundamentally the speed of response of a photodiode is limited by the time it takes photogenerated carriers to drift across the depletion region. The carriers may be assumed to travel at a constant (max.) drift velocity v_d, when the field in the depletion region exceeds a saturation value.

The longest transit time, t_{drift} is for carriers, which must traverse the full depletion layer width w and is given by

$$\boxed{t_{\text{drift}} = \frac{w}{v_d}} \qquad \text{...(9.15)}$$

The transist time through a depletion layer width of 10 μm is around 0.1 ns.

(*b*) **Diffusion time of carriers generated outside the depletion region.** Carrier diffusion us a slow process where the time taken t_{diff}, for carriers to diffuse a distance d may be written as

$$\boxed{t_{\text{diff}} = \frac{d^2}{2D_c}} \qquad \text{...(9.16)}$$

where, D_c = Minority carrier diffusion coefficient.

Example : The hole diffusion time through 10 μm of silicon is 40 ns whereas the electron diffusion time over the same distance is around 8 n sec.

(*c*) **Time constant because of the capacitance of photodiode with its load :** A reverse biased photodide shows a voltage dependent capacitance caused by variation in the stored charge at the junction. The junction capacitance C_j is given by

$$C_j = \frac{\varepsilon_s A}{w} \qquad \text{...(9.17)}$$

where, ε_s = Permittivity of the semiconductor material

A = Diode junction area

All the above factors affect the response time of the photodiode but the ultimate bandwidth of the device is limited by the drift time of carriers through the depletion region t_{drift}. In this case, let us assume that,

- no carriers are generated outside the depletion region
- Negligible junction capacitance

Then the maximum photodiode 3 dB bandwidth B_m is given by

$$B_m = \frac{1}{2\pi t_{\text{drift}}} \qquad \text{...(9.18)}$$

$$B_m = \frac{v_d}{2\pi w} \qquad \text{...(9.19)}$$

9.10.4. Noise

The overall photodiode sensitivity because of the random current and voltage fluctuations which occur at the device output terminal in both the presence and absnece of an incident optical signal.

The photodiode dark current corresponds to the level of the output photocurrent when there is no intended optical signal present. But some photogenerated currents may be there because of the presence of background radiation entering the device.

The inherent dark current can be minimized through the use of :

- High quality
- Defect free material

They reduces the number of generated carriers in the depletion region as well as those which diffuse into this layer from the p+ and n+ regions. Moreover the surface current can be minimized by

- Carefull fabrication
- Surface passivation

Because of the statistical nature of the quantum detection process, the detector average current $\bar{I}$ always exhibits a random fluctuation about its mean value. This fluctuation is known as **shot noise,** where

Mean square current variation $\overline{i_s^2} \propto \bar{I}$

and $\overline{i_s^2} \propto B$

Thus, the rms value of this shot noise current is

$$\boxed{\overline{i_s^2} = (2eB\bar{I})^{1/2}} \qquad \text{...(9.20)}$$

To access the noise performance of optical detectors, various parameters are there. Some of the commonly utilized parameters are :

- the noise equivalent power (NEP)
- the detectivity (D)
- the specific detectivity (D^*)

NEP : It is defined as the incident optical power at a particular wavelength or with a specified spectral content required to produce a photodetector current equal to the rms noise current within a unit bandwidth (*i.e.,* B = 1 Hz).

To obtain an **expression for the NEP**, we start with

$$P_0 = \frac{I_P hf}{\eta e}$$

$$\boxed{P_0 = \frac{I_P hc}{\eta e\lambda}} \quad ...(9.21)$$

Then putting,

Photocurrent, I_P = rms shot noise current

$$I_P = (2e\bar{I}B)^{1/2} \quad ...(9.22)$$

and photodiode average current,

$$\bar{I} = I_P + I_d \quad ...(9.23)$$

where, I_d = dark current within the derivce

Therefore :

$$I_P = [2e(I_P + I_d)B]^{1/2} \quad ...(9.24)$$

When $I_P >> I_d$, then

$$\boxed{I_P \simeq 2e\mathrm{B}} \quad ...(9.25)$$

Substituting the value of I_P in Eq. (9.21) and putting B = 1 Hz gives the noise equivalent power as

$$\mathrm{NEP} = P_0 = \frac{2hc}{\eta\lambda} \quad ...(9.26)$$

Above equation is valid only for ideal photodetector, when quantum efficiency η = 1.

When $I_P << I_d$, then from Eq. (9.24), the photocurrent becomes :

$$\boxed{I_P \simeq [2eI_d B]^{1/2}}$$

Hence for a photodiode in which the dark current noise is dominant (with $B = 1$). The noise equivalent power is given by

$$\boxed{NEP = P_0 \simeq hc\frac{(2eI_d)^{1/2}}{\eta e\lambda}} \quad ...(9.27)$$

The **detectivity *D*** is defined as the inverse of the *NEP*, thus

$$\boxed{D = \frac{1}{NEP}} \quad ...(9.28)$$

Considering a photodiode receiving monochromatic radiation with the dark current as its dominant noise source, then from Eq. (9.27) and (9.28), we get

$$\boxed{D = D_\lambda = \frac{\eta e\lambda}{hc(2eI_d)^{1/2}}} \quad ...(9.29)$$

Specific Detectivity (D*) : It is a parameter which incorporates the area of the photodetector A in order to take account of the effect of this factor on the amplitude of the device dark current. It is necessary when background radiation and thermal generation rather than surface conduction are the major causes of dark current. Thus the specific detectivity is given by

$$D^* = DA^{1/2}$$

$$\boxed{D^* = \frac{\eta e\lambda}{hc\left(\frac{2eI_a}{A}\right)^{1/2}}} \quad ...(9.30)$$

Above definition for D^* assumes a bandwidth of 1 Hz. Therefore the specific density over a bandwidth B would be equal to :

$$\boxed{D(AB)^{1/2}} \quad ...(9.31)$$

9.11. SEMICONDUCTOR PHOTODIODES WITH INTERNAL GAIN

9.11.1. Avalanche Photodiodes (APDs)

APDs amplify the signal during the detection process. They use a similar principle to that of "photomultiplier" tubes used in nuclear radiation detection. In the photomultiplier tube :

1. A single photon acting on the device releases a single electron.
2. This electron is accelerated through an electric field until it strikes a target material.

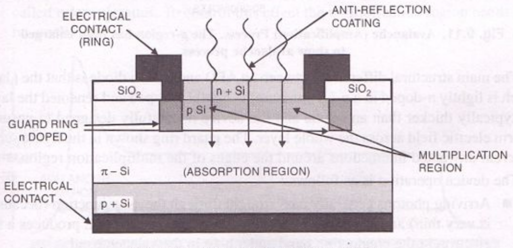

Fig. 9.10. Avalanche Photodiode (APD).

3. This collision with the target causes "impact ionisation" which releases multiple electrons.
4. These electrons are then themselves accelerated through the field until they strike another target.
5. This releases more electrons and the process is repeated until the electrons finally hit a collector element.

Thus, through several stages, one photon has resulted in a current of many electrons. APDs are of course different from photomultiplier tubes. Photomultiplier tubes are vacuum tubes with metallic targets arranged in stages down the length of the tube. APDs use the same principle but multiplication takes place within the semiconductor material itself. This process in APDs typically results in an internal amplification of between 10 and 100 times. Avalanche photodiode is shown in Fig. 9.10.

In its basic form an APD is just a *p-i-n* diode with a very high reverse bias. A reverse bias of 50 volts is typical for these devices compared with the regular *p-i-n* diodes used in the photoconductive mode which is reverse biased to only around 3 volts (or less). In the past some APDs on the market have required reverse bias of several hundred volts although recently lower voltages have been achieved.

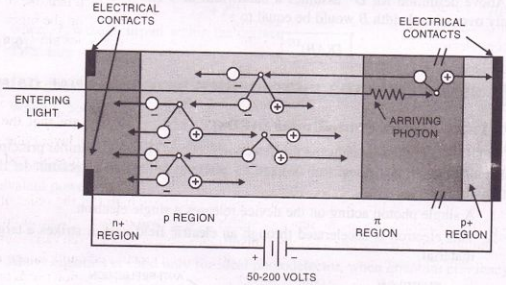

Fig. 9.11. **Avalanche (Amplification) Process. The *p*-region has been enlarged to show avalanche process.**

The main structural difference between an APD and a *p-i-n* diode is that the *i* layer (which is lightly *n*-doped in a *p-i-n* structure) is lightly *p*-doped and renamed the layer. It is typically thicker than an *i*-zone and the device is carefully designed to ensure a uniform electric field across the whole layer. The guard ring shown in the figure serves to prevent unwanted interactions around the edges of the multiplication region.

The device operation is as follows :

- Arriving photons generally pass straight through the *n+-p* junction (because it is very thin) and are absorbed in the *n* layer. This absorption produces a free electron in the conduction band and a hole in the valence band.
- The electric potential across the *n* layer is sufficient to attract the electrons towards one contact and the holes towards the other. In the figure electrons are attracted towards the *n+* layer at the top of the device because being reverse biased it carries the positive charge. The potential gradient across the *n* layer is not sufficient for the charge carriers to gain enough energy for multiplication to take place.
- Around the junction between the *n+* and *p* layers the electric field is so intense that the charge carriers (in this case electrons only) are strongly accelerated and pick up energy. When these electrons (now moving with a high energy) collide with other atoms in the lattice they produce new electron-hole pairs. This process is called **impact ionization.**
- The newly released charge carriers (both electrons and holes) are themselves accelerated (in opposite directions) and may collide again.

Both electrons and holes can now contribute to the multiplication process. However now there is a small problem. Looking at Fig. 9.11, it is obvious that when an electron ionizes an atom an additional electron and hole are produced. The electron moves to the left of the picture and the hole to the right. If the hole now ionizes an atom it releases an electron (and a hole) and the electron moves to the left and starts again.

If holes and electrons have an equal propensity for ionization we can get an uncontrolled avalanche which will never stop. Thus devices are built such that one of the charge carriers has a significantly higher propensity for ionization than the other. In silicon, electrons are the dominant carrier. In III-V alloy materials holes are often employed.

The result of the above process is that a single arriving photon can result in the production of between 10 and 100 or so electron-hole pairs.

The important things to note about the device described above are that the multiplication region is very small and absorption takes place within the *n* layer rather than near the junction. That is, the absorption and multiplication regions are separated. This is shown in Fig. 9.12. There are two important factors:

1. The strength of the required electric field is extremely high (Of the order of 10^6 volts/metre.) In the presence of such a strong field, imperfections in the multiplication region (such as lattice mismatches, impurities and even variations in dopant concentration) can produce small areas of uncontrolled multiplication called **microplazmas.** To control this effect the multiplication region needs to be small.

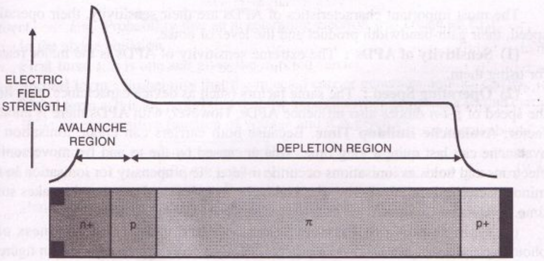

Fig. 9.12. Electric Field Strengths in an APD.

This is the reason for the guard ring mentioned above. Around the edges of the multiplication region we tend to get irregularities and imperfections in the material. Without the guard ring these serve as sites for microplazmas. In addition, to create an electric field of the required strength we need an applied bias voltage that increases with the thickness of the multiplication region. (Double the thickness of the region - double the required voltage.) High voltages (indeed voltages above about 12 volts) are expensive and difficult to handle in semiconductor devices and so we aim to minimize the applied voltage.

2. For the above reason the junction region is very thin and therefore it can't absorb many incident photons. The *n* layer is the absorption layer.
3. Many APDs are designed so that the depletion layer extends through the entire *p*-region to the *n* region boundary.

9.11.1.1. Types of Materials Used

As with *p-i-n* diodes different materials are usually employed for each of the three important wavelength bands:

(1) 800 nm to 1 Micron Band : In this band silicon is usually employed although germanium will also work reasonably well. Germanium devices however produce higher noise levels than silicon ones. As mentioned above for *p-i-n* structures, silicon has a relatively high band gap energy and is therefore used only for wavelengths shorter than about 1 micron. In practice, short wavelengths are only used for very short distance (less than 500 metres) communications. Attenuation over such short distances is generally not great enough to require the sensitivity of an APD (or to justify its cost).

(2) 1310 nm Band : This is important as it is the band used by most existing long distance communications systems. Germanium APDs are used extensively but III-V semiconductor alloys are increasing in usage because of the high noise levels in germanium.

(3) 1550 nm Band : III-V APDs are used widely in the 1550 nm band. The most common materials system in use is InGaAs/InP where the majority charge carrier is hole rather than electron.

9.11.1.2. APD Characteristics

The most important characteristics of APDs are their sensitivity, their operating speed, their gain-bandwidth product and the level of noise.

(1) Sensitivity of APDs : The extreme sensitivity of APDs is the major reason for using them.

(2) Operating Speed : The same factors (such as device capacitance) that limit the speed of *p-i-n* diodes also influence APDs. However, with APDs there is another factor: **Avalanche Buildup Time**. Because both carriers can create ionisation an avalanche can last quite a long time. This is caused by the to and fro movement of electrons and holes as ionisations occur. Provided the propensity for ionisation in the minority carrier is relatively low, the avalanche will slow and stop but this takes some time. Avalanche Buildup Time thus limits the maximum speed of the APD.

(3) Gain-Bandwidth Product : The accepted measure of goodness of a photodetector is the gain-bandwidth product. This is usually expressed as a gain figure in dB multiplied by the detector bandwidth (the fastest speed that can be detected) in GHz. A very good current APD might have a gain-bandwidth product of 150 GHz.

(4) Noise : APDs are inherently noisy as the multiplier effect applies to all free electrons including those made free by ambient heat. This is especially a problem in longer wavelength devices where the band gap energy is low. In the design of devices

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9.11.1.5. Temperature Effect on Avalanche Gain

The gain mechanism of an avalanche photodiode is very temperature sensitive because of the temperature dependence of the electron and hole ionization rates. Particularly this temperature dependence is critical at high bias voltage, when small change in temperature can cause large variations in gain. Figure 9.13 shows an example of silicon avalanche photodiode.

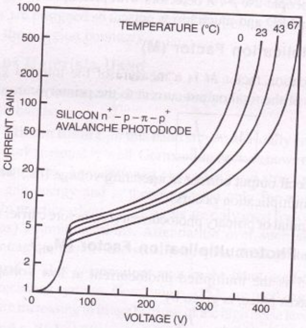

Fig. 9.13. Example of how the gain mechanism of a silicon avalanche photodiode depends on temperature. The measurements for this device were done at 825 nm.

Example : If the operating temperature decreases and the applied bias voltage is kept constant, the ionization rates for electrons and holes will increase and therefore the avalanche gain.

To maintain a constant gain when temperature varies, the electric field in the multiplying region of the pn junction must also be changed. For this receiver should have a compensation circuit which adjusts the applied bias voltage on the photodetector when temperature varies.

A simplified temperature depedent expression for the gain can be obtained from empirical relationship :

$$\boxed{M = \frac{1}{1 - \left(\frac{v}{v_B}\right)^n}} \quad \text{...(9.1)}$$

where, v_B = Breakdown voltage at which n goes to infinity

n = Varies between 2.5 to 7 depending on the material

and

$$\boxed{v = v_a - I_M R_M} \quad \text{...(9.2)}$$

where, v_a = reverse bias voltage applied to detector

I_M = multiplied photocurrent

R_M = photodiode series resistance and detector load resistance

Since the breakdown voltage is known to vary with temperature as:

$$\boxed{v_B(T) = v_B(T_0)\,[1 + a(T - T_0)]} \qquad ...(9.3)$$

The temperature dependence of the avalanche gain can be approximated by substituting Eq. (9.3) into Eq. (9.1)

$$\boxed{n(T) = n(T_0)\,[1 + b(T - T_0)]} \qquad ...(9.4)$$

The constants a and b are positive for reach through avalanche photodiodes and can be determined from experimental curves of gain versus temperature.

9.12. PHOTODIODES APPLICATIONS

Some of the photodiodes applications are :

- Laser guided missiles, Laser warning, Laser range finders
- Optical free air communication
- Automotive anti collision optical radar
- Laser alignment and control systems
- Spectral analysis (medical)
- Two colour sensor (combined with IR detector chip)
- Monitoring of Hg lamps for sterilization
- Film processing
- Flame monitoring
- Scintillator read out
- Spectral monitoring of Earth ozone layer (environmental)
- Space applications (solar sensors, star sensors)

9.13. COMPARISON OF PHOTODIODES WITH PHOTOMULTIPLIERS

Advantages compared to photomultipliers :

(1) Excellent linearity of output current as a function of incident light.

(2) Spectral response from 190 nm to 1100 nm (silicon), longer wavelengths with other semiconductor materials.

(3) Low noise.

(4) Ruggedized to mechanical stress.

(5) Low cost.

(6) Compact and light weight.

(7) Long lifetime.

(8) High quantum efficiency, typically 80%.

(9) No high voltage required.

Disadvantages compared to photomultipliers :

(1) Small area

(2) No internal gain (except avalanche photodiodes, but their gain is typically 10^2-10^3 compared to up to 10^8 for the photomultiplier)