

CHAPTER 7

PHOTODETECTORS

7.1 INTRODUCTION

Photodetectors (or photosensors) are transducers that alter one of their characteristics when light energy impinges on them. In this category, *photoresistors* alter their ohmic resistance, *rods* and *cones* of the retina neurons of the eye alter their electrochemical response, and chlorophyll in plant leaves alters the rate of converting CO₂ to O₂. Some other photodetectors alter the flow of electrical current or the potential difference across their terminals.

Photodetectors with sufficiently fast response that provide a measurable output for a small amount of light, are easily reproducible, and are economical are worth investigating for applications in high-speed optical communications. This category includes avalanche photodiodes (APDs) and positive intrinsic negative photodiodes (PINs).

7.2 PHOTODETECTOR CHARACTERISTICS

Photodetectors are characterized by certain key parameters. Among them are *spectral response*, *photosensitivity*, *quantum efficiency*, *dark current*, *forward-biased noise*, *noise equivalent power*, *terminal capacitance*, *timing response* (rise time and fall time), *frequency bandwidth*, and *cutoff frequency*.

- Spectral response relates the amount of current produced with wavelength, assuming that all wavelengths are at the same level of light.
- Photosensitivity is the ratio of light energy (in watts) incident on the device to the resulting current (in amperes).

- Quantum efficiency is the number of generated electron–hole pairs (i.e., current) divided by the number of photons.
- Dark current is the amount of current that flows through the photodiode in the absence of any light (dark), when the diode is reverse-biased. This is a source of noise when the diode is reverse-biased.
- Forward-biased noise is a (current) source of noise that is related to the shunt resistance of the device. The shunt resistance is defined as the ratio voltage (near 0 V) to the amount of current generated. This is also called *shunt resistance* noise.
- Noise equivalent power is defined as the amount of light (of a given wavelength) that is equivalent to the noise level of the device.
- Terminal capacitance is the capacitance from the p–n junction of the diode to the connectors of the device; it limits the response of the photodetector.
- Timing response of the photodetector is the time for the output signal to climb from 10% to 90% of its amplitude (rise time) and to drop from 90% to 10% (fall time).
- Frequency bandwidth is the frequency (or wavelength) range in which the photodetector is sensitive.
- Cutoff frequency is the highest frequency (wavelength) at which the photodetector is sensitive.

In the following, we examine the PIN and the APD photodiodes.

7.3 THE PIN PHOTODIODE

The PIN photodiode is a semiconductor device that consists of an intrinsic (lightly doped) region that is sandwiched between a p-type and an n-type layer. When this device is reverse-biased, it exhibits an almost infinite internal impedance (i.e., like an open circuit), with an output current that is proportional to the input optical power.

The input–output relationship defines a *responsivity* R and a *quantum efficiency* η as follows:

$$R = \frac{\text{output current } I}{\text{input optical power } P} \text{ (amperes/watts)} \quad (7.1)$$

$$\eta = \frac{\text{number of output electrons}}{\text{number of input photons.}} \quad (7.2)$$

R and η are related through the relationship

$$R = \frac{e\eta}{h\nu}, \quad (7.3)$$

where e is the electron charge, η is the efficiency, h is Planck's constant, and ν is the light frequency.

When a photon creates an electron–hole pair, the device produces a current pulse with duration and shape that depends on the response time of the device.

The RC time constant determines the frequency response of the PIN device. The capacitance of the reverse-biased PIN photodiode is a limiting factor to its response (and switching speed). As the switching speed increases to very high frequencies, parasitic inductance becomes significant and causes “shot noise,” which is estimated as

$$2e(I_s + I_{\text{dark}}), \quad (7.4)$$

where I_s is the signal current and I_{dark} the current that flows at the absence of signal, or *dark current*.

7.4 THE APD PHOTODIODE

The APD is a semiconductor device that, when reverse-biased, creates strong fields in the junction region. When a photon causes an electron–hole pair, the pair flows through the junction. Because of the strong fields in the junction, the electron gains enough energy to cause secondary electron–hole pairs, which in turn cause more. Thus a multiplication (or avalanche) process takes place (hence the name), and a substantial current is generated from few initial photons.

The gain M of an APD is expressed by

$$M = \frac{I_{\text{APD}}}{I_{\text{primary}}}, \quad (7.5)$$

where I_{APD} is the APD output current and I_{primary} is the current due to photon–electrons conversion. However, during this multiplication process, shot noise is multiplied as well, and is estimated as

$$2eIM^2F, \quad (7.6)$$

where F is the APD noise factor.

If τ is the effective transit time through the avalanche region, the APD bandwidth is approximated as:

$$B_{\text{APD}} = \frac{1}{2pM\tau}. \quad (7.7)$$

EXERCISES

1. Name two natural and two artificial photosensors.
2. What factor limits the switching speed of a PIN diode?
3. An APD diode has very little gain. True or false?