Photodiode Characteristics

Module 3

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1 Objectives

This module describes and explains the main electrical and optical photodiode characteristics. The reader will gain an appreciation for the various characteristics and how they effect device performance. After reading this module, the reader will:

- Understand the basic electrical and optical characteristics of a photodiode.
- Acknowledge that the characteristics will change as the doping profile of the diode changes.
- Understand how changes in conditions such as bias and temperature effect the diode characteristics.

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2 Electrical Charcateristics

2.1 Equivalent Circuit

The equivalent circuit model of a photodiode is shown in Fig. 1. The photocurrent generated by the incident radiation, is represented by an ideal current source. The n^+-p junction is represented by an ideal diode. Junction capacitance (see Section 2.1.1), parasitic capacitance (see Section 2.1.2), shunt resistance (see Section 2.1.3) and series resistance (see section 2.1.4) are modelled using capacitors and resistors respectively. The various currents and voltages associated with the photodiode are indicated on the diagram.

2.1.1 Junction Capacitance

As seen in Module 1, the separation of charge in the depletion region of a p-n junction is equivalent to a parallel plate capacitor across the junction. Since all

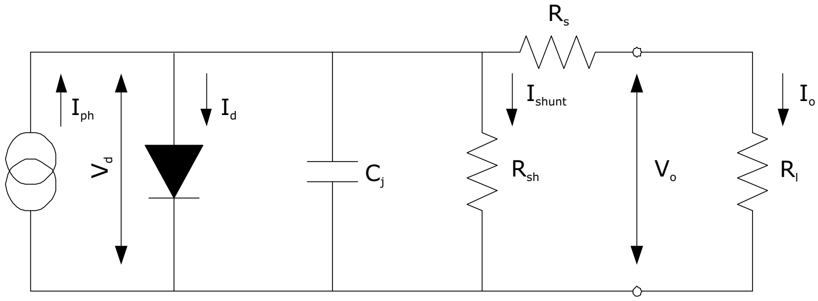

Figure 1: Photodiode equivalent circuit.

photodiodes are essentially p-n junctions, a photodiode will always have an associated junction capacitance. The area of the parallel plates of the capacitance corresponds to the area of the depletion region, while the separation between the plates is the depletion region length. From Module 1 we have that the capacitance is given by:

$$C = \frac{\varepsilon_0 \varepsilon_r A}{W} \tag{1}$$

where ϵ_0 is the permittivity of a vacuum, ϵ_r is the relative permittivity of silicon of the semiconductor and A and W are the area and depletion region length respectively. The junction capacitance varies with the applied bias, decreasing as the reverse bias increases since the length of the depletion region increases as reverse bias increases.

2.1.2 Parasitic Capacitance

The parasitic or stray capacitance C_s is due to bondpad capacitances, package capacitances and any other stray capacitances which may arise. C_s is usually approximated by:

$$C_s = C_{bp} + C_p \tag{2}$$

where C_{bp} is the bondpad capacitance and C_p is the package capacitance. Both bondpad capacitance and package capacitance are usually measured.

2.1.3 Shunt Resistance

Shunt resistance, R_{sh}, is the slope of the current-voltage characteristic of the photodiode (see Section 2.2) at the origin. R_{sh} is calculated using the dark current I_{dark} (see Section 2.2.3) measured with the diode biased at -10 mV, i.e.,

$$R_{sh} = \frac{0.01}{I_{dark}}\ \Omega \tag{3}$$

2.1.4 Series Resistance

A photodiode has an associated series resistance due to contact resistance and bulk semiconductor resistance. The series resistance is usually in the order of 10s to 100s of Ohms and is given by:

$$R_s = \frac{(S - W)\,\rho}{A} + R_{contact} \tag{4}$$

where S is the silicon substrate thickness, W is the length of the depletion region, ρ is the resistivity of the substrate, A is the area of the depletion region and $R_{contact}$ is the contact resistance.

2.1.5 Output Current

Using the equivalent circuit of Fig. 1, the output current, I_0, can be written as:

$$I_0 = I_{ph} - I_d - I_{shunt} \tag{5}$$

I_d can be written using the ideal diode equation (see Module 1) giving:

$$I_0 = I_{ph} - I_{sat}\left(e^{\frac{qV_d}{\eta kT}}\right) - I_{shunt} \tag{6}$$

where I_{sat} is the saturation current, which refers to the almost constant current that flows when an ideal diode is reverse biased, V_d is the bias applied to the diode, q is the charge on an electron, k is Boltzmann's constant and T is the temperature of the photodiode in Kelvins. η is a material dependent constant known as the ideality factor. The ideality factor determines the shape of the current-voltage characteristic (see Section 2.2) of a diode at very low current levels. For pure silicon η is 2 for low currents and drops to 1 as the current starts to rise [1].

2.2 Current-Voltage Characteristics

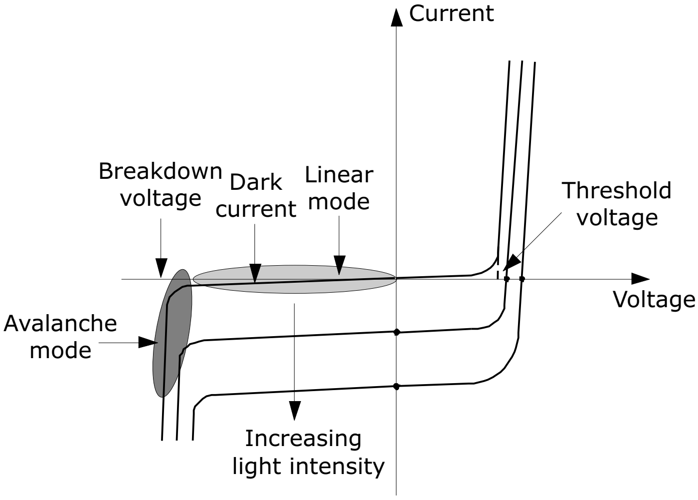

Figure 2: The current-voltage characteristics of a diode biased in linear and avalanche mode.

The current-voltage (I-V) characteristics of a photodiode are shown in Fig. 2. Fig. 2 shows the I-V characteristic of the detector operated below the breakdown voltage (see Section 2.2.1) in linear and avalanche mode. In the dark the characteristic is similar to that of an ideal diode. In linear mode when light strikes the photodiode, the I-V characteristic shifts downwards by the amount of photocurrent generated. Increasing the light intensity causes further shifts in the sensitivity. In avalanche mode, regardless of the light intensity the current increases significantly as the bias approaches the breakdown voltage. Fig. 3 shows the I-V characteristic of the detector biased above the breakdown voltage in Geiger-mode. When the detector is biased above the breakdown voltage, breakdown will not occur until one or more carriers injected or generated within the high field region initiates a self-sustaining avalanche current. The reverse current-voltage characteristic (shown in Fig. 3) exhibits two branches when the detector is operated in Geiger-mode. In the upper branch 'on state' an avalanche current in the milliamp range flows corresponding to a self-sustained avalanche process. In the

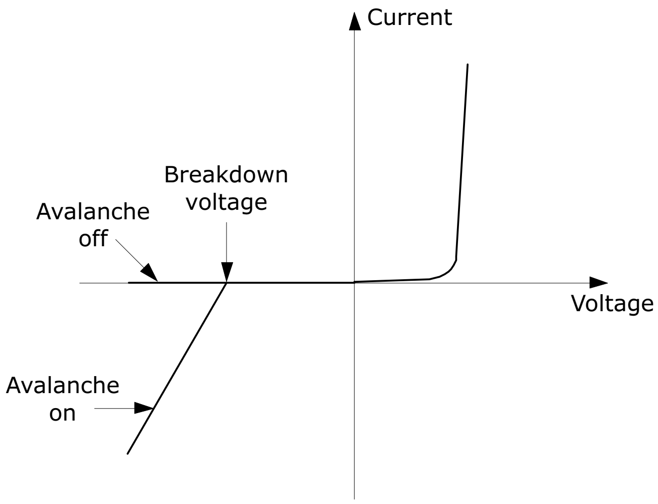

Figure 3: The current-voltage characteristics of a diode biased in Geiger mode.

lower branch 'off state' the avalanche process has not yet been triggered and no current flows. When a carrier succeeds in triggering the avalanche the current switches to the 'on' value. In the case of photogenerated carriers, the leading edge of the avalanche pulse marks the arrival time of the detected photon. The avalanche current continues to flow until an external circuit quenches the diode, by lowering the bias voltage below the breakdown voltage.

2.2.1 Breakdown Voltage

The breakdown voltage, (V_{br}), also known as the maximum reverse voltage, is the highest reverse bias that can be safely applied to a photodiode before the diode junction undergoes avalanche breakdown. At V_{br} there is a very sharp increase in current and the breakdown voltage is often specified as the reverse bias voltage at which the dark current (see Section 2.2.3) reaches a value of $1\ \mu$A or $10\ \mu$A. The Breakdown voltage will depend on the doping profile of the diode. For example, the breakdown voltage of a linearly graded p-n junction (see Module 1) is given by:

$$V_B = \frac{4\varepsilon_m^{3/2}}{3}\left(\frac{2\varepsilon_0\varepsilon_r}{q}\right)^{1/2}(a)^{-1/2} \qquad (7)$$

where a is the impurity gradient and ε_m is the maximum electric field.

2.2.2 Threshold Voltage

The threshold voltage, V_t, is the forward bias required to reach the region of upward swing, or the linear region, of the forward characteristic [1]. The threshold voltage is found by fitting a linear function to the linear part of the forward characteristic and establishing where this linear function crosses the x-axis.

2.2.3 Dark Current

The photodiode dark current, I_{dark}, is the leakage current that flows when the diode is in the dark and reverse biased. Dark current increases with increasing reverse bias and increasing temperature. Increases with reverse bias are slight, however, increases with temperature may be substantial with dark current approximately doubling for every 10 °C rise in temperature.

2.3 Timing Response

A photodiode will always have a response speed associated with it. This response speed relates to the amount of time a photodiode needs to respond to a change in light level. The speed of response varies according to the biasing mode of the diode. Details of the responses for the different modes of operation are given below:

2.3.1 Linear and Avalanche Mode:

When biased in linear or avalanche mode the speed of response of a diode is generally expressed as the rise time, t_r, or cutoff frequency, f_c. The rise time is defined as the time required for the output signal to rise from $10\ \%$ to $90\ \%$ of the final value. The cutoff frequency or bandwidth, on the other hand, is the frequency at which the output decreases by 3 dB. The relationship between t_r

and f_c may be roughly approximated by:

$$f_c = \frac{0.35}{t_r}. \tag{8}$$

The bandwidth has two main components:

1. f_{RC}: the bandwidth associated with the RC time constant.

2. $f_{transit}$: the bandwidth associated with the carrier transit time.

The RC time constant bandwidth, f_{RC}, is given by:

$$f_{RC} = \frac{1}{2\pi RC} \tag{9}$$

where R is the sum of the series resistance, R_s, and load resistance R_l and C is the total capacitance, including junction, bondpad and package capacitance.

The transit time bandwidth varies depending on the photodiode bias. A diode biased in the linear mode has a transit time bandwidth given by:

$$f_t = \frac{0.44}{t_t} \tag{10}$$

where the transit time, t_t, refers to the time needed for the carriers to cross the depletion region. This time is generally very small, (picoseconds), and can be calculated using:

$$t_{transit} = \frac{W}{\upsilon_{sat}} \tag{11}$$

where υ_{sat} is the saturation velocity of the carriers (1×10^7 cm/s for silicon at 300 K). The transit time bandwidth for a diode biased in avalanche mode is given by:

$$f_t = \frac{1}{t_{eff}} \tag{12}$$

where $t_{eff} = t_a + t_h + t_m$. The transit time is now included in t_{eff} as, t_a - the time taken for an electron to transit the absorption region ($t_a = l_a/\upsilon_{sat}$ where l_a is the length of the absorption region), t_h - the time taken for generated holes to transit both the absorption and gain region ($t_h = W/\upsilon_{sat}$) and t_m - the time taken for electrons to transit the gain region. t_m is known as the avalanche multiplication build-up time and can be considered to be the effective transit time of the electrons in the multiplication region.

Regardless of bias, the overall bandwidth of a photodiode is approximated by root-sum-squaring the individual bandwidth limitations. The photodiode bandwidth is therefore given by:

$$f_c = \frac{1}{\sqrt{\left(\frac{1}{f_{RC}}\right)^2 + \left(\frac{1}{f_t}\right)^2}} \tag{13}$$

The bandwidth of a photodiode will also be limited by diffusion time which relates to the collection time of the carriers generated outside the depletion region in the bulk semiconductor. These carriers experience no electric field and may not be detected for several nanoseconds, or even microseconds, slowing the response considerably. Photodiodes are generally designed so that most carriers are generated in the depletion region. Efforts are also made to keep junction, bondpad and package capacitance to a minimum to avoid a large RC time constants. Through careful design very fast diodes may therefore be developed.

2.3.2 Geiger Mode

The timing response of a photodiode biased in Geiger-mode is the time difference between the arrival of a photon and its detection through the generation of an avalanche current. This is a statistical process and thus the timing response leads to a distribution function. The timing response of the device is typically quoted as the full-width at half maximum (FWHM) of this distribution function. Transit time and diffusion time together with the time taken for the multiplication to spread through the diode determine the timing response (see Module 5 for a more detailed explanation). Typical timing response for silicon diodes is between 100 and 200 ps.

3 Optical Characteristics

3.1 Quantum Efficiency and Responsivity

The quantum efficiency of a photodiode is defined as:

$$\eta = \frac{number\ of\ e - h\ pairs\ produced}{number\ of\ incident\ photons} \tag{14}$$

where $0 \leq \eta \leq 1$. Photons incident on the semiconductor will be absorbed with depth, x, into the device such that the total power absorbed is [2]:

$$P_{abs}(x) = P_{inc}(1 - R)(1 - e^{-\alpha x}) \tag{15}$$

where P_{inc} is the incident optical power, and $R = (n_1 - n_2)^2/(n_1 + n_2)^2$ is the normal incidence surface reflectance at the air/semiconductor interface, leading to typical Fresnel reflection losses of $\sim 32\%$. The values n_1 and n_2 are the refractive indices of air and the semiconductor respectively, while α is the absorption coefficient of the semiconductor material and $1/\alpha$ is the penetration depth. The penetration depth is the point where $1/e$ of the incident optical power remains.

The number of photons absorbed is the total absorbed power divided by the photon energy, $E = h\nu$. If every absorbed photon were to generate an e-h pair then the quantum efficiency for a semiconductor with a surface reflectance of R and an absorption coefficient α is simply [2]:

$$\eta = (1 - R)(1 - e^{-\alpha x}) \tag{16}$$

A useful figure of merit to describe the performance capability of the photodiode is its responsivity, $\Re$, which is the ratio of the photocurrent to the incident optical power and is given by:

$$\Re = \frac{I_{photo}}{P_{opt}} = \frac{\eta q}{h\nu}\ [A/W] \tag{17}$$

For an ideal photodiode one electron should flow in the external circuit for every incident photon. In practice the quantum efficiency is limited by several factors such as incomplete absorption, recombination, surface reflection and contact shadowing. The limits imposed on the quantum efficiency also limit the device responsivity.

It is important to note that the responsivity will also vary with wavelength. The responsivity is higher at longer wavelengths since the photon energy is reduced and hence there are more available photons per watt of incident optical power than at shorter wavelengths.

3.2 Photon Detection Probability

When biased in Geiger mode the optical response of a photodiode is generally characterised by its photon detection probability (PDP) or quantum detection efficiency (QE). The photon detection probability is the product of the device quantum efficiency with the avalanche initiation probability. It is therefore wavelength dependent. The PDP is the ultimate sensitivity of the device to photons of a specific energy. To increase the PDP one needs to increase the quantum efficiency (by adding an anti-reflection coating, for example) or increase the avalanche initiation probability (by ensuring the peak electric field in the device is as close as possible to the critical breakdown field).

4 Summary

Various photodiode characteristics have been explained and quantified. Factors impacting the characteristics have been outlined. The effect of bias on photodiode characteristics has been especially highlighted. To enhance the understanding of this module, the reader should now perform the I-V characteristic section of Experiment 2.

5 Acknowledgements

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[2] S.B. Alexander. Optical communication Receiver Design. *SPIE Press*, 1997.