Introduction to Optical Detectors (Nofziger)

Optical detectors are at the heart of most modern-day optical systems. They have largely replaced the human eye or photographic film as the detection medium.

They may be categorized into two main types—point detectors and array detectors. A point detector (individual detector) is used to measure the total amount of light in an optical beam—motion sensors, bar code scanners, etc. An array detector is used in optical systems where an image needs to be detected—digital cameras (visible light), thermal cameras (infrared energy), CCD cameras used on telescopes, etc. In actuality, array detectors are made up of individual point detectors. When you buy a 5-megapixel camera, you are actually buying 5 million individual point detectors (regularly spaced very closely in an array!).

Detectors may further be categorized into thermal and photon detectors. Thermal detectors operate by absorbing all of the light energy incident on the detector, and produce a corresponding temperature increase in some material. In turn, the temperature increase is sensed as a change in resistance, voltage, current, capacitance, etc. Thermal detectors produce an output that is directly proportional to the power Φ (joules/sec) incident on the detector.

Photon detectors operate by absorbing some of the light energy incident on the detector, and produce a corresponding electrical current. Photon detectors produce an output that is directly proportional to the photon flux Φ_{ph} (number of photons/second) incident on the detector.

In this lab we will measure the basic properties of the most commonly-used kind of photon detector—the silicon photovoltaic detector.

Basic Physics of Photovoltaic Detectors

(Information in this section is borrowed from the OPTI 400/500 class notes, "Radiometry, Sources, and Detectors" Optical Sciences Center, Dr. James Palmer)

The most popular photon detector is the photovoltaic detector, which involves an internal potential barrier. The most common barrier is formed with a p-n junction in semiconductor materials. If two adjacent regions in the same semiconductor crystal are doped such that one is n-type (donor) and the other is p-type (acceptor), then a potential barrier is formed at the junction. In the n-type material (donor, dopants are As, Sb, P), the electrons are the majority carriers and the holes are the minority carriers. In the p-type material (acceptor, dopants are Al, B, In, Ga), the holes are the majority carriers and the electrons are the minority carriers. Majority carriers are far more mobile than are minority carriers, and they are the primary contributors to current flow.

During the process of junction formation, the following events occur:

1. Free electrons in the n-region are attracted to the positive charge in the p-region, and they drift on over.
2. Free holes in the p-region are attracted to the negative charge in the n-region, and they drift on over.
3. This carrier drift leaves the n-region with a net positive charge and the p-region with a net negative charge. The whole crystal stays neutral; no net carriers are gained or lost.
4. A potential barrier is thus formed at the junction between the p-region and the n-region.

Fabrication

A p-n junction photodiode may be fabricated by one of several techniques. The most common is to start with an n-type of material and diffuse a p-type region through an oxide window as shown below in Fig. 1.1.

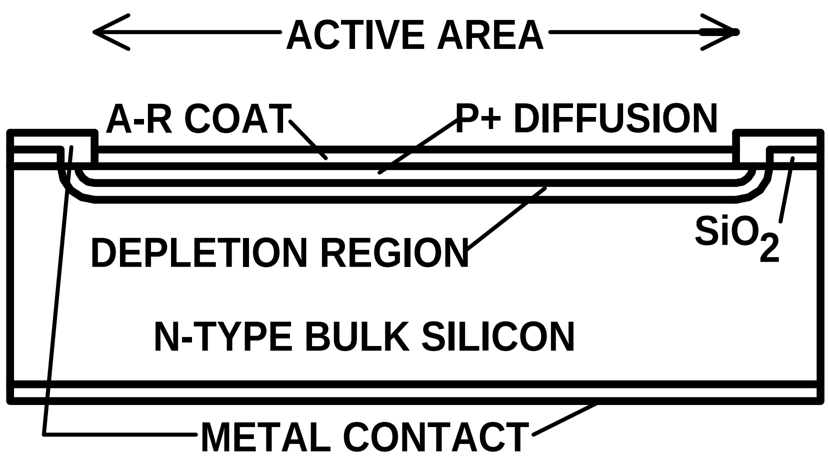

Fig. 1.1 Diffused p-n junction photodiode.

Barrier Height, Energy Gap, and Cut-off Wavelength

The barrier height depends upon the donor and acceptor levels and concentrations. This structure is shown in Figure 1.2. The region between the n-type and the p-type is called the depletion region, and there is an electric field across it.

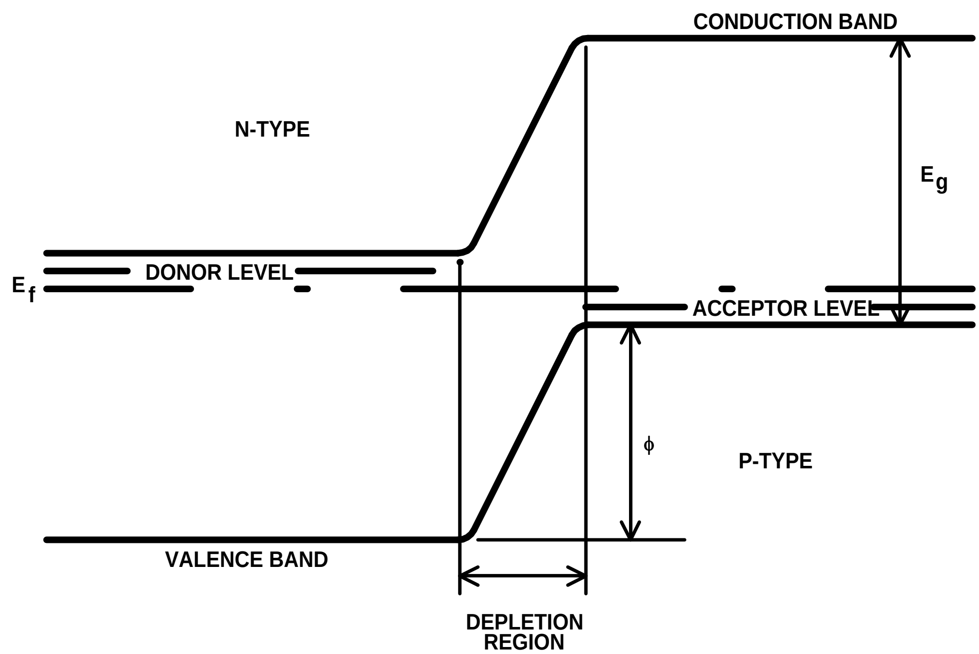

Fig. 1.2 Energy levels in a p-n junction.

The difference in energy between the bottom of the conduction band and the top of the valence band is called the energy gap, E_g. Incident photons with energy > E_g create electon-hole pairs, primarily within the depletion region. The longest wavelength at which this process can occur is the cutoff wavelength λ_c:

$$\lambda_c = \frac{1.2398}{E_g} \qquad (\lambda \ in \ \mu m, \ E_g \ in \ eV) \tag{1-1}$$

Note that for silicon, E_g = 1.12 eV, and the cutoff wavelength is 1100 nm.

Biasing the Junction

If we apply external bias across the junction, we can change the energy level structure. If we apply FORWARD BIAS, where the positive terminal of the bias source (shown here as a battery) is applied to the p-type region, the barrier height is reduced by the amount of applied voltage. The positive terminal of the bias source attracts carriers from the other side of the junction (n-type) and vice versa. The consequence is a high current flow due to conduction by majority carriers. Since the barrier height is lowered, the depletion region becomes narrower.

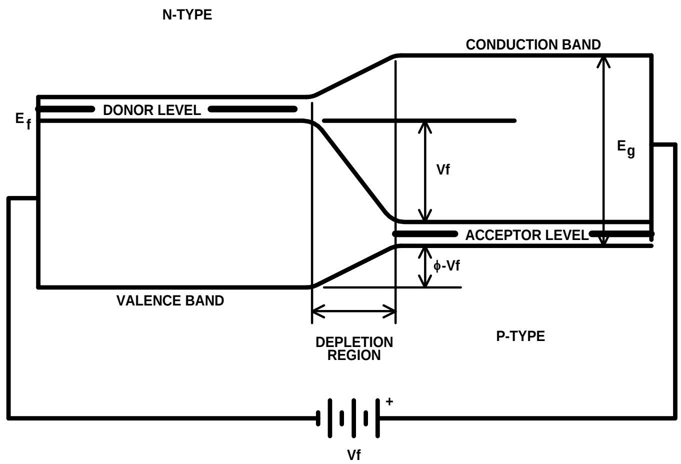

Fig. 1.3 Application of forward bias to a p-n junction.

If we apply REVERSE BIAS, where the positive terminal of the bias source (shown here as a battery) is applied to the n-type region, the barrier height is increased by the amount of applied voltage. The positive terminal of the bias source repels carriers from the other side of the junction (n-type) and vice versa. The consequence is a low current flow due to conduction by minority carriers. Since the barrier height is increased, the depletion region becomes wider.

The advantage of reverse-biasing a photodiode is to greatly increase its speed of response to high-frequency time-varying (AC) signals.

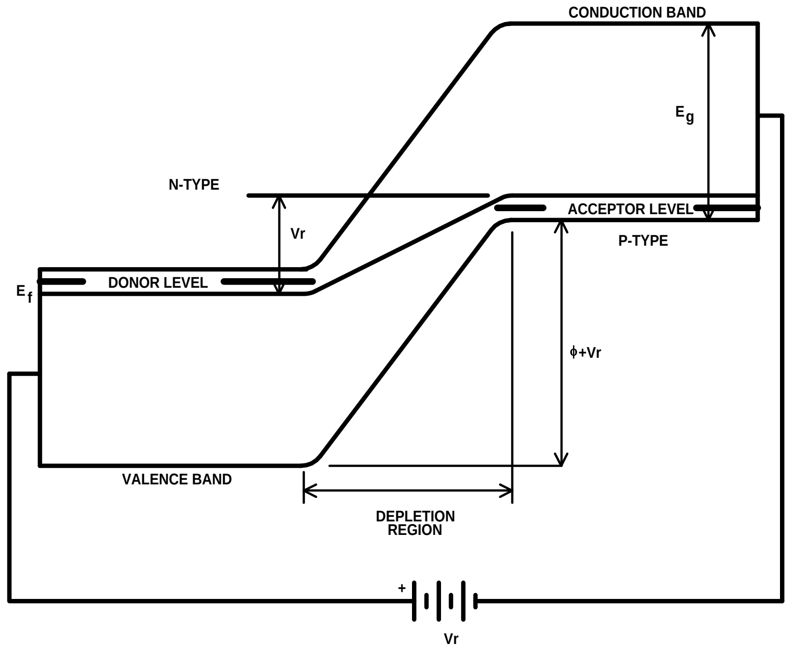

Fig. 1.4 Application of reverse bias to a p-n junction.

Current-Voltage Characteristics of a p-n Junction

The equation of the I-V (current-voltage) characteristics of a p-n junction is derived from a continuity equation:

$$I = I_o\left(e^{\frac{qV}{\beta kT}} - 1\right) \tag{1-2}$$

where q = electronic charge = 1.60217733 x 10^{-19} C
k = Boltzmann constant = 1.380658 x 10^{-23} J/K
T = absolute temperature in Kelvins
q/(kT) = 38.7 at 300K
β = “constant” to make the equation fit the data; varies with applied voltage, usually 1 but as high as 3; sometimes called the ‘ideality’ factor
Io = reverse saturation current

With optical radiation incident, a current is generated, which adds to the dark current as:

$$I = I_o\left(e^{\frac{qV}{\beta kT}} - 1\right) - I_{ph} \tag{1-3}$$

I_{ph} is called the photocurrent, and is given by:

$$\boxed{I_{ph} = \eta \cdot q \cdot \Phi_{ph} = \eta \cdot q \cdot \left(\frac{\lambda}{hc} \right) \cdot \Phi} \qquad (1\text{-}4)$$

where:
- η is the quantum efficiency of the detector (independent of wavelength)
- λ is the wavelength of the light on the detector
- h is Planck's constant (6.626×10^{-34} J·sec)
- c is the speed of light
- Φ_{ph} is the photon flux (photons/sec) on the detector
- Φ is the power (in watts) of the light on the detector

The photocurrent generated by the incident radiation is directly proportional to the photon flux Φ_{ph}, reduced by the quantum efficiency. This says that a photovoltaic detector is a quantum, or photon detector. Every photon absorbed within the depletion region is converted into an electron (electron-hole pair) that contributes to the photocurrent.

The same photon flux Φ_{ph} at two different wavelengths will produce the same photocurrent.

At a given wavelength, the current is also directly proportional to the incident power Φ, also reduced by the quantum efficiency. However, at two different wavelengths, the same power incident on the detector will NOT produce the same photocurrent. This is simply a consequence of the fact that a photodiode is a photon detector. The conversion of photon flux to optical power scales with wavelength:

$$\Phi = \Phi_{ph} \cdot (\textit{energy per photon}) = \Phi_{ph} \cdot (h\nu) = \Phi_{ph} \cdot \left(\frac{hc}{\lambda} \right) \qquad (1\text{-}5)$$

The same optical power Φ at two different wavelengths will NOT produce the same photocurrent. Rather, the photocurrents will be in direct proportion to the two wavelengths.

A typical set of I-V curves for various incident levels of Φ is shown in Figure 1.5.

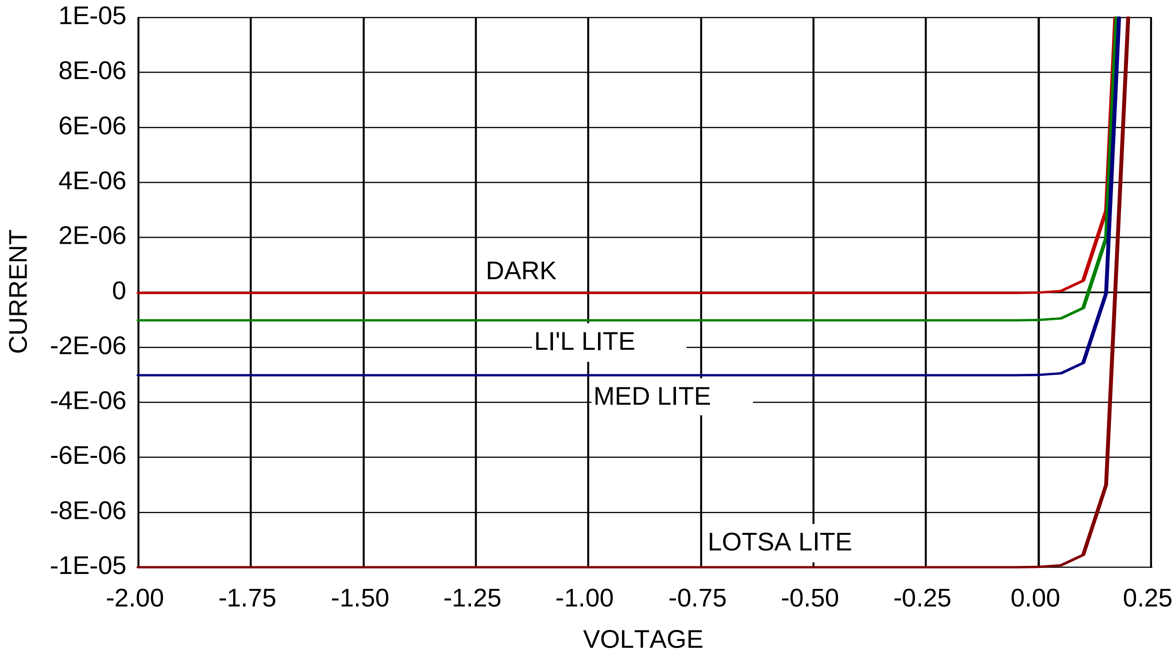

Fig. 1.5 I-V curves for a photodiode with several light levels.

Modes of Operation

There are several ways in which one can operate a photovoltaic detector:

- Short-circuit current. If we set V = 0 in the I-V equation, the result is that $I = -I_{ph}$ which is linear with radiant power. This linearity is easily demonstrated up to 7 decades in radiometric-quality silicon photodiodes. This is the most important and useful way to operate a photodiode for radiometric and photometric applications.

- Open-circuit voltage. Set I = 0 in the I-V equation and solve for V:

$$V_{oc} = \frac{\beta kT}{q} \ln\left(\frac{I_o + I_{ph}}{I_o} \right) \qquad (1\text{-}6)$$

If $I_{ph} >> I_o$, the result is that V_{oc} is logarithmic with radiant power. This is typically not as useful as the short-circuit mode of linear operation.

In this lab, we will learn how to operate a photodiode in the short-circuit current mode, and demonstrate its linear response to light.

Responsivity

One of the most useful merits of operation is the detector's responsivity, **R**. This is defined as the output photocurrent divided by the input optical power (amps/watt):

$$R \equiv \frac{I_{ph}}{\Phi} = \eta q \frac{\lambda}{hc} \qquad (1\text{-}7)$$

This can be plotted vs. wavelength. The ideal photovoltaic detector ($\eta = 1$) has a spectral responsivity proportional to wavelength out to the cutoff wavelength, λ_c, which is determined by the energy gap (see equation 1-1).

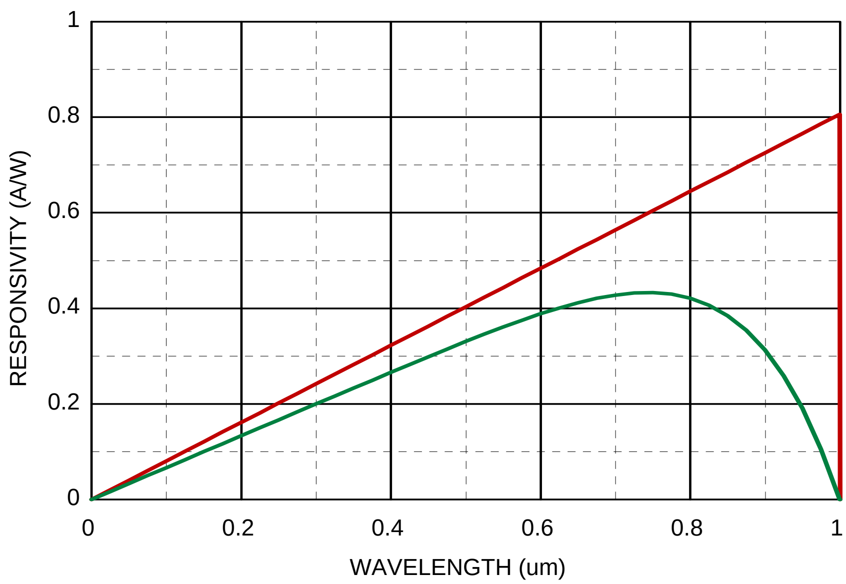

Fig. 1.6 Responsivity vs. wavelength—ideal (upper curve) and actual (lower curve).

Photovoltaic Detector Interfacing—The Transimpedance Amplifier

The following circuit is used to operate a photovoltaic detector (also called a photodiode). The circuit is known as a Transimpedance Amplifier, or "TIA" for short. It is the "interface" between the photodiode and the electronics used to measure the output signal. Fundamentally, it converts the photocurrent, I_{ph} to a voltage, V_o.

The photodiode is connected between the inverting pin of the op-amp (pin 2) and ground, and the non-inverting pin (pin 3) is tied directly to ground. (Note that ground refers to the ground terminal of the power supply that supplies power to this entire circuit.) The op-amp works to maintain a voltage difference of 0 volts between pins 2 and 3, which means that $\Delta V=0$ across the photodiode. This operates the photodiode in the short-circuit mode, which means that the photocurrent is linear with optical power.

The relationship between I_{ph} and the output voltage is linearly related to the feedback resistor R_f, and follows Ohm's Law:

$$V_o = -I_{ph} \cdot R_f \tag{1-8}$$

The feedback resistor determines the gain of the current-to-voltage conversion process.

The negative sign indicates that the output voltage is negative for a positive photocurrent, or positive for a negative photocurrent. Physically, this is because the photodiode is connected to the inverting pin of the op-amp. (Note that the sign of the photocurrent may be changed by simply reversing the detector leads within this circuit.)

Substituting from equation (1-4) gives the following system equation for the TIA:

$$\boxed{V_o = -\left(\frac{\eta \cdot q}{hc}\right) \cdot \lambda \cdot \Phi \cdot R_f} \tag{1-9}$$

Note that $\left(\frac{\eta \cdot q}{hc}\right)$ is a constant. The remaining terms are variable and directly determine the voltage measured at the output of the TIA (pin 6).

Please note the following:

- The output voltage is directly proportional to the power of the incident light.

- The output voltage is directly proportional to the value of the feedback resistor, which is user-selectable. On most commercial TIA's, there is a range switch that allows you to select different values of R_f, typically 10^3, 10^4, 10^5, 10^6, or 10^7 ohms. The switch will be labeled as either "Ohms" or "Volt/Amp".

- The maximum gain available is determined by the power supply voltage to the op-amp, $\pm V_{cc}$. You must keep $V_o < |\pm V_{cc}|$ or the circuit will saturate (V_o will no longer increase with increasing photocurrent). In saturation, your readings will no longer be valid!

- Saturation of the photocurrent itself occurs at a current density of 50 $\mu A/mm^2$ for silicon photodiodes. NOTE: the area to consider is the area of the light beam incident on the detector (not necessarily the area of the detector itself). In other words, the photocurrent will saturate locally within the depletion region.

- The output voltage is directly proportional to the wavelength of the incident light. If 1 watt of light from a He-Ne laser (633nm) falls on the detector, compared to 1 watt of light from a He-Cd laser (442nm), the output of the TIA will be (633/442) times higher for the red light compared to the violet light.