

# Photometer and Optical Link

## Purpose

You will design and build a photometer (optical detector) based on a silicon photodiode and a current-to-voltage amplifier whose output is proportional to the intensity of incident light. First, you will use it to measure the room light intensity. Then you will set up and investigate an optical communication link in which the transmitter is a light emitting diode (LED) and the receiver is your photodiode detector.

## Introduction

Experiment 6 demonstrates the use of the photodiode, a special p-n junction in reverse bias used as a detector of light. The incoming light excites electrons across the silicon band gap, producing a current proportional to the incident optical power. We will also introduce a number of "photometric" quantities that are widely used in optoelectronics.

## Readings

1. Data sheets for the PD204-6C/L3 silicon photodiode and the EFR5365S AlInGaP light emitting diode are available at the course web site.
2. See H&H Section 15.15 to learn how a lock-in amplifier works. For a lot more detail, see this link: <http://www.thinksrs.com/downloads/PDFs/ApplicationNotes/AboutLIAs.pdf>
3. Optional reading on diodes: FC Chapter 4, particularly Sections 4.18 & 4.19
4. For general background on optoelectronics, see H&H Section 9.10.

## New Apparatus and Methods

### PHOTODIODE

The PD204 photodiode used in this experiment is a p-intrinsic-n (PIN) silicon diode operated in reverse bias. A sketch of the photodiode structure is shown in Figure 6.1. The very thin p-type conducting layer acts as a window to admit light into the crystal. The reverse bias voltage maintains a strong electric field throughout the intrinsic region forming an extended depletion layer. The depletion layer should be thicker than the absorption length for photons in silicon in order to maximize the efficiency. Any incident photon whose energy exceeds the band-gap energy is

absorbed to produce an electron-hole pair by photoelectric excitation of a valence electron into the conduction band. The charge carriers are swept out of the crystal by the internal electric field to appear as a photocurrent at the terminals. The photocurrent is proportional to light intensity over a range of more than 6 orders of magnitude.

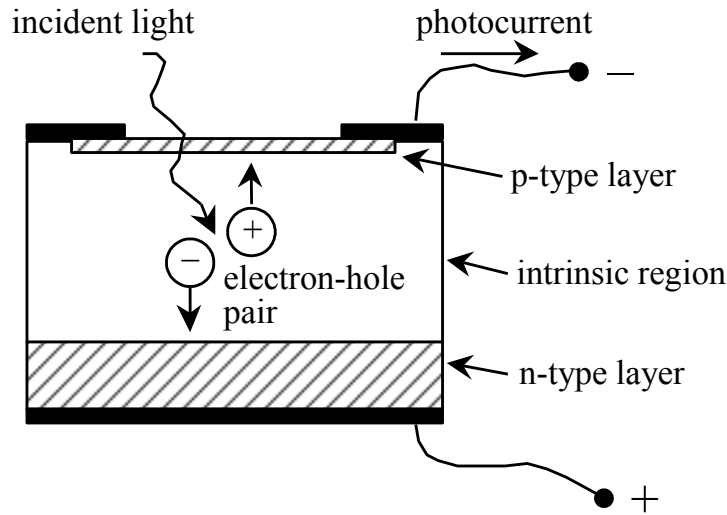


Figure 6.1 Structure of the photodiode.

## LIGHT EMITTING DIODE

The EFR5365S light emitting diode acts electrically just like any diode. It emits light when forward-biased due to direct radiative recombination of electrons and holes. The forward voltage drop is about 1.9 V rather than 0.6 V because the LED is made of AlInGaP instead of silicon.

## **Theory**

### CURRENT-TO-VOLTAGE AMPLIFIER

In an ordinary inverting amplifier (Exp. 4, Figure 4.3) the input voltage is applied to a resistor, and the amplifier generates an output voltage in response to the current that flows through the input resistor to the virtual ground at the negative op-amp input. A current-to-voltage amplifier (Figure 6.2) is an inverting amplifier with the input current  $I_{in}$  applied directly to the negative op-amp input. Since no current flows into the op-amp input, the output voltage must be  $V_{out} = -I_{in}R_F$ . The ideal low-frequency gain of a current-to-voltage amplifier is

$$G = \frac{V_{out}}{I_{in}} = -R_F. \quad (1)$$

This gain has the units of impedance i.e, Ohms, and it is often called a trans-impedance or trans-impedance gain. The current-to-voltage amplifier is sometimes called a trans-impedance amplifier.

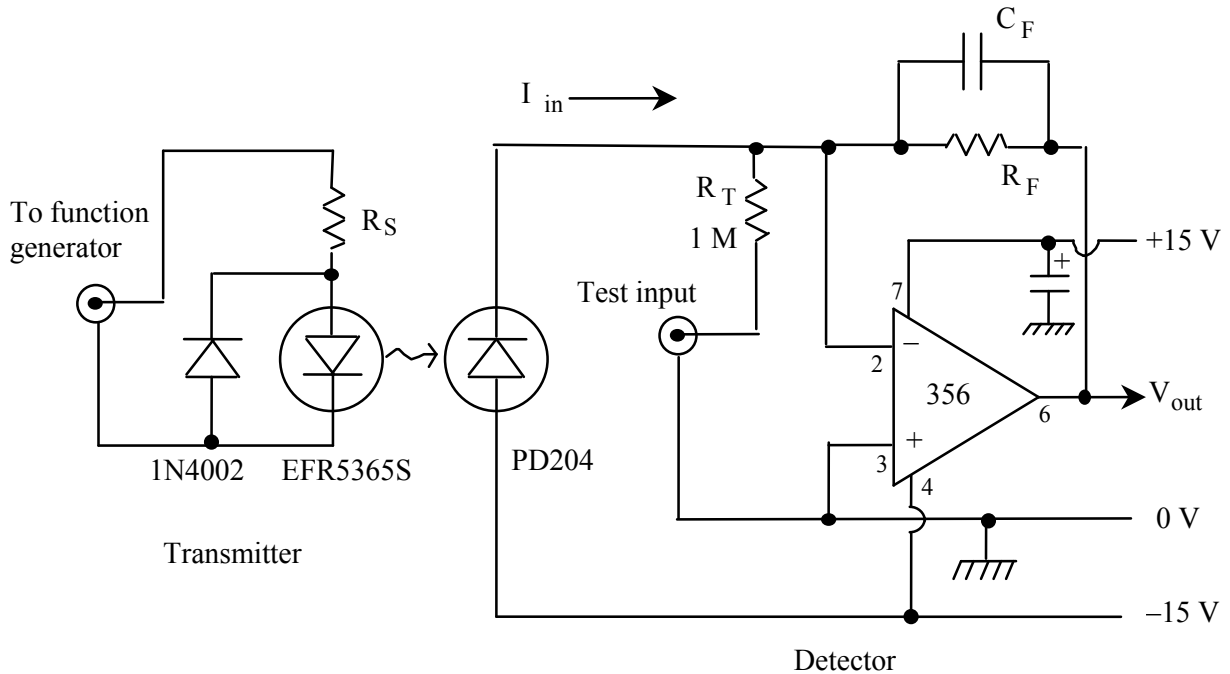


Figure 6.2 Light transmitter and photodiode detector.

In our photometer circuit the current  $I_{in}$  flows through the back-biased photodiode when it is illuminated (its sign is negative, so it actually flows out of the op-amp negative input node and the resulting  $V_{out}$  is positive). The  $1\text{ M}\Omega$  resistor can be used to inject a test current, and the feedback capacitor  $C_F$  enhances stability i.e., it helps to avoid spontaneous oscillations of the op-amp. This capacitor is often needed in photodiode amplifiers to compensate for the relatively large capacitance of the photodiode.

### PHOTODIODE SENSITIVITY

The photodiode sensitivity  $S_\lambda$  (in units of  $\mu\text{A}/(\text{mW}/\text{cm}^2)$ ) is defined as the photocurrent per unit light intensity incident on the photodiode. It is a function of the light wavelength  $\lambda$ . For light intensity  $N$  (in  $\text{mW}/\text{cm}^2$ ) the photocurrent  $I$  (in  $\mu\text{A}$ ) is given by

$$I = S_\lambda N. \quad (2)$$

The sensitivity at any wavelength  $\lambda$  is given on the data sheet in terms of the peak sensitivity  $R_{940\text{nm}}$  at 940 nm times a correction factor called the relative spectral sensitivity, or RSR:

$$S_{\lambda} = R_{940\text{nm}} \text{RSR}(\lambda). \quad (3)$$

## LED OUTPUT

To describe the output of a light source like our LED, it is helpful to introduce the notion of solid angle. Consider a transparent sphere of radius  $r$ , and suppose that an area  $A$  on the surface of the sphere is painted black. We then say that the blacked out region subtends a solid angle of  $\Omega$  steradians (str), where  $\Omega = A/r^2$ . According to this definition, the whole sphere subtends a solid angle of  $4\pi$  str. One steradian is an area of  $r^2$ , just as one radian is an arc of length  $r$ .

The concept of solid angle is essential in separating the two units in which light is customarily measured. Both the lumen and the candela originated in the 18th century when the eye was the primary detector of electromagnetic radiation.

The lumen (lm) is a measure of the total light power emitted by a source. You might then expect that there is a conversion factor between lumens and Watts, and you would be right: its value is 683 lm/Watt. However, things are a bit more complicated because this conversion factor is only correct for light with a wavelength of 555 nm, the yellow-green color that our eyes are most sensitive to. For other colors the conversion factor is multiplied by a dimensionless number  $y(\lambda)$  called the photopic standard luminosity function (an Excel file with a tabulation of this function can be found on our web site). A rough plot of  $y(\lambda)$  is shown in Figure 6.3. The point of this is that two sources described by the same number of lumens (the same “luminous flux”) will have the same subjective brightness to a human observer. This kind of color corrected unit is very helpful if you want to design a control panel with lots of colored lights, and you want them all to have the same perceived brightness. To summarize, if the luminous flux of your source is described as  $F$  lumens, then you convert this to Watts using this formula:

$$F(\text{W}) = \frac{1}{683 \cdot y(\lambda)} F(\text{lm}) \quad (4)$$

Notice that more Watts are required for a given luminous flux as the color gets farther and farther away from yellow-green, to make up for the declining sensitivity of the eye.

However, this is not the whole story for describing light sources, because the amount of light emitted varies with direction, and how much light we intercept in a given direction will depend upon how much solid angle our detector covers. Thus we need a measure of light power per solid angle, and this unit is called the candela, equal to one lumen/str. A light source that emits one

candela in every direction emits a total of  $4\pi$  lumen, since there are  $4\pi$  str in the whole sphere. The quantity measured by the candela is called the “luminous intensity”. If you look at the data sheet for our EFR5365S LED you will see that it uses the unit “mcd” or millicandela to describe the brightness. The values given are for light emitted along the axis of the LED. For other directions see the Spatial Distribution graph in the data sheet. By dividing Eqn. 4 above by the solid angle we can rewrite it as a relation between the luminous intensity  $J$  in mcd and the power per unit solid angle:

$$J(\text{mW/str}) = \frac{1}{683 \cdot y(\lambda)} J(\text{mcd}) \quad (5)$$

Suppose now we place our photodiode a distance  $r$  from the LED, and we want to find the intensity  $N(\text{mW/cm}^2)$  at the photodiode. We first find  $J$  in millicandela on the LED data sheet. We then convert  $J(\text{mcd})$  to  $J(\text{mW/str})$ , using Equation 5 and  $y(\lambda)$  for the appropriate wavelength. (For our LED,  $y(635 \text{ nm})=0.217$ .) Finally we divide  $J(\text{mW/str})$  by  $r^2$  to get  $N(\text{mW/cm}^2)$ .

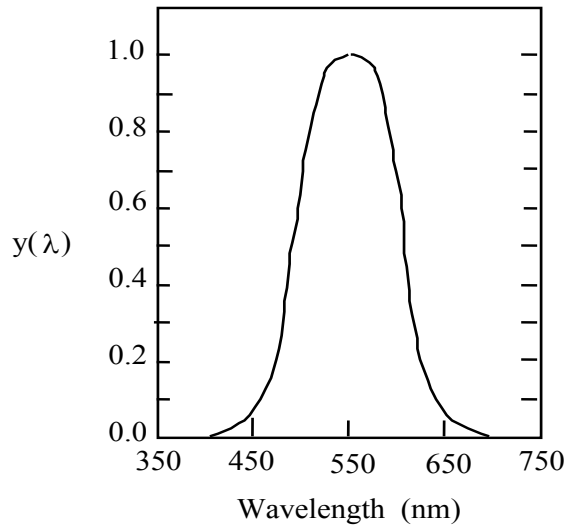


Figure 6.3 Standard luminosity function

## Prelab Problems

- (A) (1 point) Estimate the sensitivity  $S_\lambda$  (in units of  $\mu\text{A}/(\text{mW}/\text{cm}^2)$ ) of the PD204 photodiode to the fluorescent lights in the lab. See the photodiode data sheet posted on the course web site. You will have to estimate the mean wavelength of the white fluorescent lights. See Figure 6.3, and assume that the lights do not emit much radiation that is outside the wavelength range visible to the eye and inside the wavelength range that the photodiode can sense.

(B) (1 point) What intensity of white light (in  $\text{mW}/\text{cm}^2$ ) do you expect is incident on your photodiode on the lab bench when it is facing upwards i.e., towards the fluorescent lights? Each fluorescent light tube produces approximately 4W of visible light. You can assume that half of it ( $\sim 2\text{W}$ ) is emitted downwards into  $2\pi$  str.
- (2 points) For the current-to-voltage amplifier in Figure 6.2, choose a value for the feedback resistor  $R_F$  so that an incident white-light intensity  $N$  of  $1.0 \text{ mW}/\text{cm}^2$  produces an output voltage of 10 V. The small feedback capacitor  $C_F$  is used to suppress spontaneous oscillations. The trans-impedance gain of the amplifier at any particular frequency is  $-Z_F$ , where  $Z_F$  is the effective impedance of the parallel  $R_F C_F$  circuit. Show that the gain rolls off at high frequencies with a bandwidth of  $f_B = 1/(2\pi R_F C_F)$ . The bandwidth will suffer if  $C_F$  is too large. What is the bandwidth  $f_B$  if  $C_F = 10 \text{ pF}$ ?
- (A) (1 point) Write down the dc values of the voltages at the + and – inputs and at the output of the op-amp for zero light on the photodiode. The diode data sheet gives the diode dark current.

(B) (1 point) What would the voltages be if the photodiode leads were accidentally reversed to make it forward biased? In this case the diodes acts like a short circuit.
- (A) (1 point) Assume we have an EFR5365S LED being run with a current of 20 mA as in Figure 6.2. See the LED datasheet on the course website. Compute the intensity  $N$  (in units of  $\text{mW}/\text{cm}^2$ ) incident on a detector 15 cm away placed at the center of the transmitted beam.

(B) (1 point) Compute the expected output voltage from the optical receiver under these conditions. Remember to recalculate the sensitivity of the detector for the wavelength of light from the LED.
- (2 points) To drive the transmitter, the function generator will be adjusted to produce a square wave with a high level of 10 V (unloaded) and a low level of 0 V. The high-level should give 20 mA forward current in the LED, and the low level should give 0 mA. Find the value of the series resistor  $R_S$  that gives the correct current. Look on the data sheet to find the LED forward voltage drop at 20 mA. Do not forget that when the unloaded output of the function generator is set to 10 V, the loaded output will be lower because of the  $50 \Omega$

output impedance.

## **Experiment**

### 1. PHOTOMETER

Build the photometer circuit shown in Figure 6.2. Use a value for  $R_F$  close to what you found in prelab problem 2, and a few pF of capacitance  $C_F$  across the feedback resistor to avoid spontaneous oscillations. Pay attention to the direction of the photodiode. To start, you do not need to connect the function generator or the  $1\text{ M}\Omega$  test resistor, but you should use this path if you find your photodetector circuit is not working and you want to test your op amp setup. Your circuit is probably working if you get a positive voltage out that varies as you block and unblock your photodiode.

Measure the average intensity of light from the fluorescent lamps in the lab from the output of your photometer circuit. How does your result compare with your prelab estimate? Keep in mind that the estimate you made of the light intensity was very rough, and also note that the data sheet only gives a “typical” value of the sensitivity of the photodiode.

The intensity of solar radiation on a clear day is about  $1\text{ kW/m}^2$ . How does this compare with the average light intensity in the lab?

### 2. OPTICAL COMMUNICATION LINK

Set up a light emitting diode type EFR5365S as the transmitter on a separate small circuit board about 5 cm away from your photodetector, and drive it with the signal generator. Be sure to protect the LED with a series resistance that prevents the forward current exceeding 30 mA. Also, connect a rectifier diode in parallel with the LED but with opposite polarity. This will prevent you from accidentally running the LED at with a large negative bias voltage, causing it to break down. Place the LED transmitter 15 cm from the photodiode and orient both elements to be coaxial so as to maximize the amount of light detected. You can check alignment by using a piece of white paper to see if the red illumination is centered on your photodiode detector.

Before connecting it to the LED transmitter circuit, set up the function generator to produced 1 kHz square waves with the upper voltage level at 10V and the bottom voltage at 0V. You accomplish this by using the DC offset setting of the function generator. Now connect the function generator output to the LED transmitter circuit. Observe the input driving signal and the output of the receiver on the scope using dc coupling for both signals initially. Make sure the received signal is due to the

red light by blocking the beam for a moment. The few pF of capacitance you have placed across RF should avoid overshoot at the leading edge of the square wave.

Measure the intensity of the transmitted light and compare with your prediction. Note that the data sheet gives a minimum and typical value of the LED intensity, but no maximum, and note again that the photodiode sensitivity is only specified by a “typical” value.

Examine the rise time of the received square waves. From this, estimate the upper 3dB bandwidth of the communication link.

### 3. LOCK-IN AMPLIFIER

Finally, we will look at detection using a lock-in amplifier. First, work with your own LED circuit close to your detector. Then, at the end of the lab is a common LED source; use this as a source far from your photo-detector.

- By direct measurement, what is the smallest signal you can detect on the lock-in?
- Similarly, what is the smallest signal you can detect by looking at the output of your photodiode amplifier on the scope? If you are far away from the LED can you see the signal on the scope at all?

General lock-in instructions: For the signal input to the lock-in, choose CHANNEL A and set the adjacent switch accordingly. Trigger the lock-in by running a cable from the SYNC of your function generator (or the long sync cable from the end of the room) to the REFERENCE INPUT of the lock-in amplifier. Set the switches above this input to “f” and “positive square”. Increase the lock-in SENSITIVITY as much as possible without overloading the input. Set the output expand to x1 and the pre- and post-filter time constants to 1 second. Adjust the lock-in phase setting to get maximum signal. You can change any of these settings later to see what happens. Work with the room lights on and a signal frequency of around 1 kHz.