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 radiation energy excites electrons across the silicon band gap, producing a current or a pulse of charge proportional to the incident energy deposited in the detector.

In this experiment we will introduce a number of "photometric" quantities that are widely used in opto-electronics. At the end of the lab, you will use a lock-in amplifier to extract a weak signal from noise.

Readings

For general background on opto-electronics, see H&H Section 9.10. All of the detailed information you will need for this experiment is given below. Data Sheets for the PD204-6C silicon photodiode and the MV5752 GaAsP light emitting diode are available at the course web site. The manual for the SR510 lock-in amplifier is also posted at the web site.

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 if 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.

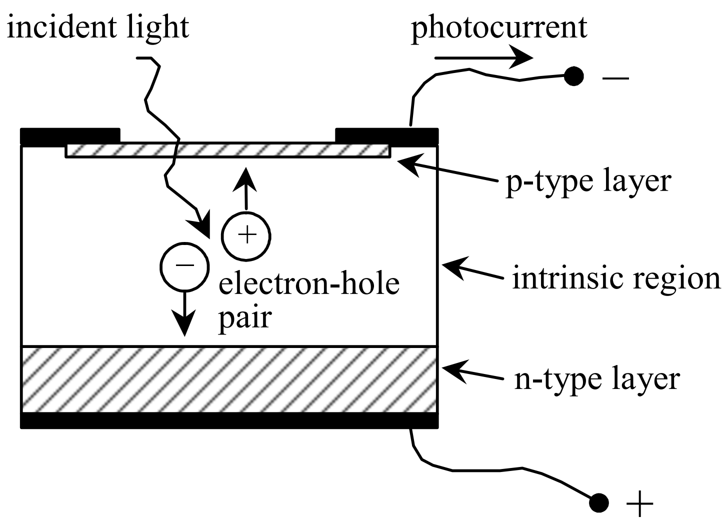

Figure 6.1 Structure of the photodiode.

LIGHT EMITTING DIODE

The MV5752 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 1.7 V rather than 0.6 V because the LED is made of GaAsP instead of silicon.

LOCK-IN AMPLIFIER

The lock-in amplifier is a highly sensitive AC voltmeter which can detect sinusoidal signals as small as a nanovolt, even in the presence of strong interference. You must provide it with a reference sine or square wave that is coherent with the signal you want to detect (same frequency and constant phase difference). The lock-in then averages away everything in the signal except what is coherent with the reference wave. After sufficient averaging time, interfering signals will be averaged away and the desired signal will remain. The display on the lock-in reads the rms voltage of the desired signal. A very simple example of a lock-in is described in H&H Section 15.15. You can read more about the lock-ins we have in the lab (Stanford Research SR510) in the manual which is posted on our course web site.

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

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

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

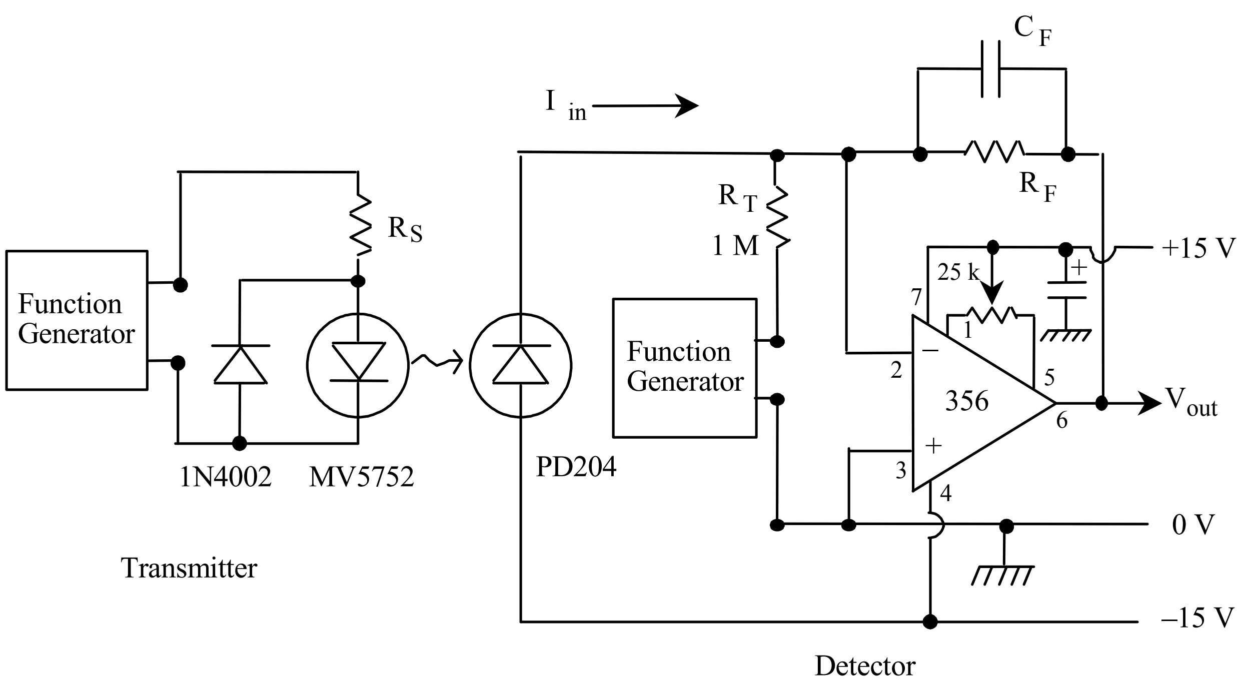

Figure 6.2 Light transmitter and photodiode detector. The trim pot between pins 1 and 5 can be adjusted to compensate for any output voltage offset in the op-amp.

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 MΩ resistor is used to inject a test current, and the feedback capacitor enhances stability.

PHOTODIODE SENSITIVITY

The photodiode sensitivity S_λ (in units of μA/(mW/cm^2)) is defined as the photocurrent per unit light intensity incident on the photodiode. It is a function of the light wavelength λ. Thus for light intensity N(in mW/cm^2) the photocurrent I (in μA) is given by

$$I = S_\lambda N. \tag{2}$$

The sensitivity at any wavelength λ is given on the data sheet in terms of the peak sensitivity at 940 nm times a correction factor called the relative spectral sensitivity, or RSR:

$$S_\lambda = R_{940\,\mathrm{nm}} RSR(\lambda). \tag{3}$$

The peak sensitivity may be taken from data-sheet information on the 'reverse light current.'

LED OUTPUT

To describe the output of a light source like our photodiode, 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 Ω steradians (str), where $\Omega = A/r^2$. According to this definition the whole sphere subtends a solid angle of 4π 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 used for light with a wavelength of 550 nm, the yellow-green color that our eyes are most sensitive to. For other colors the conversion factor is multiplied by a dimensionless number RR(λ) called the relative response of the adjusted human eye. A rough plot of RR(λ) 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, even if they are of different colors. 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:

$$F(\mathrm{W}) = \frac{1}{683 \cdot RR(\lambda)} F(\mathrm{lm})) \tag{4}$$

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 π lumen, since there are 4 π 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 MV5752 LED you will see that it uses the unit "mcd" or millicandela to describe the brightness. The values given are for a forward current of 20 mA and light emitted along the axis of the LED. For other directions you multiply by the Relative Intensity given in Fig. 3 of the data sheet.

Suppose we place our photodiode a distance r from the LED, and we want to find the intensity N(mW/cm^2) at the photodiode. According to the above definitions, we have:

$$N(\mathrm{mW/cm^2}) = \frac{1}{683 \cdot RR(\lambda)} \frac{1}{(r(\mathrm{cm}))^2} J(\mathrm{mcd}) \tag{5}$$

For our red LED, RR(635 nm)=0.2. Remember that *J* depends on the LED current and on direction.

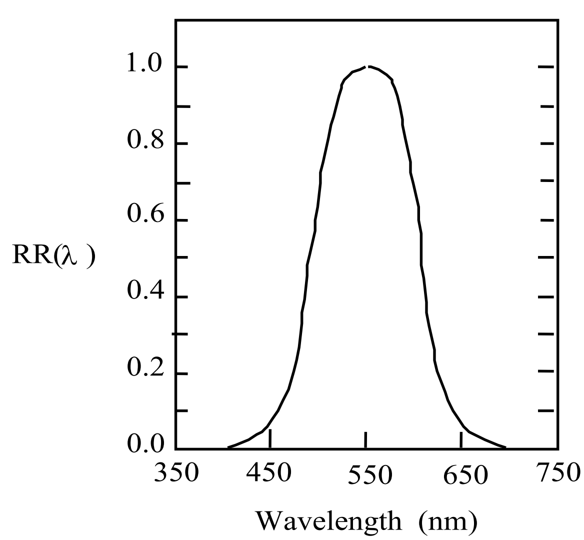

Figure 6.3 Relative response of adjusted human eye

Problems

1. Estimate the sensitivity S_λ (in units of μA/(mW/cm^2)) of the PD204-6C photodiode to the fluorescent lights in the lab. See the photodiode data sheet posted on the course web site. For this estimate you can suppose that the fluorescent lights in the lab emit 550 nm light, since they are designed for human vision.

2. For the current-to-voltage amplifier in Figure 6.2, choose a value for the feedback resistor R_F so that 550 nm light intensity N of 1.0 mW/cm^2 produces an output voltage of 10 V. The small feedback capacitor C_F is used to suppress spontaneous oscillations. The bandwidth will suffer if C_F is too large. What is the bandwidth f_B if C_F = 10 pF? Use the formula $f_B=1/(2\pi R_F C_F)$.

3. 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. What would the voltages be if the photodiode leads were accidentally reversed to make it forward biased?

4. For the light transmitter in Figure 6.2, compute the intensity N(in units of mW/cm^2) of light incident on a detector 5 cm away placed at the center of the transmitted beam. Assume there is a current of 30 mA flowing through the LED. See the LED data sheet posted on the course web site. 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.

5. The transmitter will generate square waves. The high-level should give 30 mA forward current in the LED, and the low level should give 0 mA. These two levels should correspond to 7.5 V and 0 V unloaded output from the function generator. 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 30 mA. Do not forget that when the unloaded output of the function generator is set to 7.5 V, the loaded output will be lower because of the 50 Ω output impedance.

Experiment

PHOTOMETER

Build the photometer circuit shown in Figure 6.2. Null the op-amp output voltage by adjusting the 25 kΩ trimpot when the photodiode is blacked out and the input test current is set to zero.

Test the amplifier using the test current source (R_T and the function generator) with the photodiode still covered. Verify that the ac gain for 1 kHz square waves is correct. If the amplifier goes into spontaneous oscillations, suppress these with a few pF of trimming capacitor C_F across the feedback resistor. Now uncover the photodiode and remove the 1 MΩ resistor from the circuit.

Measure the average intensity of light from the fluorescent lamps in the lab. (As in the prelab, suppose the lights emit 550 nm radiation.) The intensity of solar radiation on a clear day is about 1 kW/m^2. What fraction of this is the average light intensity in the lab? There is a calibrated light meter in the lab that you can use to check the sensitivity of your circuit. We recommend that you aim both the photodiode and the meter at a sheet of white paper placed flat on the bench which is well exposed to the room light. Does your photometer have the sensitivity you predicted?

OPTICAL COMMUNICATION LINK

Set up a light emitting diode type MV5752 as the transmitter on a separate small circuit board 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, to prevent negative voltage excursions that can break down the LED if greater than 5 volts. Place the LED transmitter 5 cm from the photodiode and orient both elements to be coaxial so as to maximize the amount of light detected.

Drive the transmitter with 1 kHz square waves from the generator, using the dc offset to keep the output above ground. 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. If there is overshoot on the leading edge of the square wave, you can trim it out with a few pF of capacitance across R_F. A pair of twisted insulated wires makes a convenient capacitance (about 0.5 pF per twist—check it on the capacitance meter).

Measure the intensity of the transmitted light and compare with your prediction. Check the intensity of the LED with the calibrated digital photometer. How do the LED intensity and photodiode sensitivity compare with the data sheet claims? Use your data to refine your previous estimate of the white light intensity in the lab.

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

LOCK-IN AMPLIFIER

Finally, attach the lock-in amplifier in parallel with the scope. 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 TRIG OUTPUT of your function generator 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 should find that this occurs when the phase setting is close to 90 degrees. 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.

- What is the smallest signal you can detect on the scope?
- What is the smallest signal you can detect on the lock-in?
- How far away can you place the transmitter from the receiver and still detect the light signal with the lock-in? Make sure your signal is really due to light by blocking the path between transmitter and receiver.