

# OPTI 202L – Lab 11

## Photoconductors and Basic Electrical Measurements

### Learning Objectives

Learn how to use:

- a breadboard to build electronic circuits.
- the Wavetek 85XT hand-held digital multi-meter (DMM) to measure V and  $\Omega$ .
- the Agilent HP34401 digital multi-meter (DMM) to measure V and  $\Omega$ .

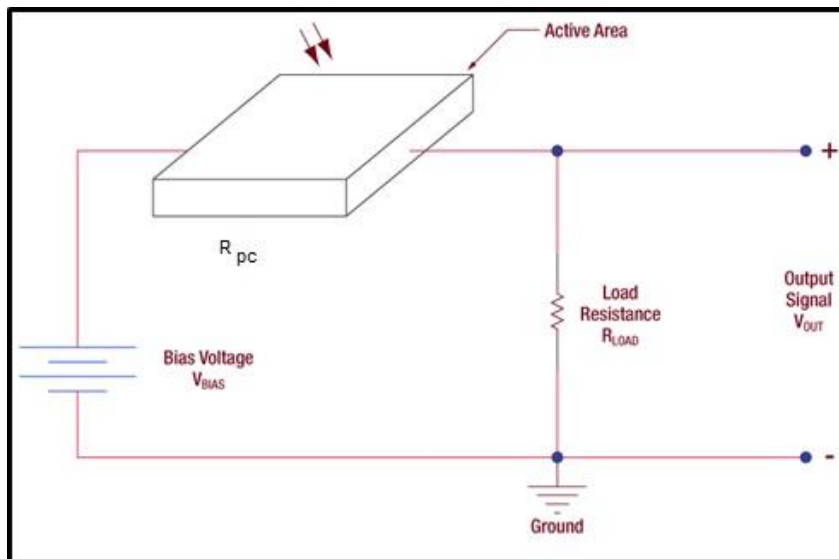
### Reading Assignment:

- Review your class notes on photoconductors from OPTI 240.
- [“Photoconductive Cells”](#)

### Pre-Lab Questions:

- (PL1) In a qualitative way, how does the conductivity  $\sigma$  of a photoconductor vary with light level  $\phi_e$  and why?
- (PL2) From the handout "Photoconductive Cells" look up the resistance,  $R_{PC}$ , of "Type 3 @ 25°C" semiconductor material at light levels of 0.1 fc, 1.0 fc, and 10 fc. (In their graph of "Resistance vs. Illumination" use the curve on the bottom)

Assuming the Bias Voltage (the supply voltage) is +10V and  $R_{LOAD} = 1000 \Omega$ , calculate  $V_{OUT}$  for these 3 light levels. (*see the last page of our Lecture Notes for help with this*)



- (PL3) What property makes "Type 3" material useful in situations where you want the circuit to sense light in a way similar to the human eye?

## Theory:

(The following is taken from Optical Radiation Detectors, Dereniak and Crowe, 1984, Ch. 4):

“A photoconductor exhibits a change in conductance (resistance) when radiant energy (photons) is incident upon it. The radiant energy increases the conductance by producing more carriers in the detector. A photoconductor is operated in a mode in which an applied electric field produces a current that is modulated by additional carriers produced by photon excitation, that is, radiation quanta are absorbed and free (photogenerated) charge carriers are generated in the semiconductor. These additional carriers cause an increase in the conductivity of the semiconductor. This phenomenon is called photoconduction.

.....

“Photoconductors are made from semiconductor materials. The spectral responsivity is determined by the energy gap. Only photons that have energies greater than the energy gap will be absorbed and cause current to flow. Free carriers are produced only when the radiation photons have sufficient energy to cause electrons to cross the energy gap. Therefore, there is a limit on the wavelength response to which a given semiconductor will detect radiation.”

“The minimum optical frequency,  $\nu$ , photon that will produce a free electron from the covalent bond is  $\nu = \frac{E_g}{h}$ . If one writes this limiting condition in terms of wavelength,  $\lambda_c = \frac{1.24}{E_g}$

where  $\lambda_c$  = maximum wavelength of radiation to produce an electronic transition

$E_g$  = energy gap in eV.

“The mechanism of semiconductor photodetection can be explained by a discussion of the energy-band theory of semiconductors and the interaction of the radiation with the carriers in the detector. In solid-state theory the energy levels of the outer electrons of an atom are spread into nearly continuous bands by interaction with the neighboring atoms in the solid. Intrinsic semiconductors are characterized by a lattice in which all of the outer (valence) electrons are bound in covalent bonds. If ejected from a covalent bond, an electron will be in an essentially neutral environment and can thus become mobile and conduct current; the vacancy (hole) left by the electron also has mobility. If an electric field is applied, any free electrons will move in one direction and the corresponding holes in the valence band will move in the opposite direction.”

“Mathematically one can express the conductivity ( $\text{ohm}^{-1} \text{cm}^{-1}$ ) of a photoelectric semiconductor device which is not illuminated as:

$$\sigma_o = N_o \mu_e q + P_o \mu_h q$$

where  $N_o$  and  $P_o$  = free carrier concentrations of electrons and holes, respectively ( $\text{cm}^{-3}$ )

$\mu_e$  and  $\mu_h$  = mobilities of electron and holes ( $\text{cm}^2 \text{sec}^{-1} \text{V}^{-1}$ )

q = charge on electron,  $1.6 \times 10^{-19} \text{C}$

If  $\Delta N$  and  $\Delta P$  are the concentrations of excess electrons and hole carriers generated by the absorption of photons, the conductivity expression will be:

$$\sigma_o = q[\mu_e(N_o + \Delta N) + \mu_h(P_o + \Delta P)]$$

The effect of this excess carrier concentration is to raise the conductivity thus producing a viable detection mechanism for absorbed radiation. Conceptually, there is a constant conductivity term and a varying conductivity term.”

$$\sigma = \sigma_o + \Delta\sigma$$

**NOTE:** In our lab this week, we will be using steady-state illumination (constant amounts of light). This will produce a change in conductivity  $\Delta\sigma$  but it will not be a time-varying change.

(It would be a time-varying change if you were trying to measure a time-varying amount of light.)

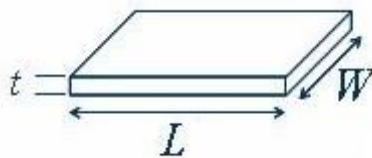
“It is more conventional to use resistance (instead of conductivity) from an engineering view-point. Therefore, the resistance of the detector geometry shown in the following figure can be expressed as:”

$$R_d = \frac{W}{\sigma L t}$$

where  $L$  = length of photoconductor (distance between electrodes)

$\sigma$  = conductance (ohm cm)<sup>-1</sup>

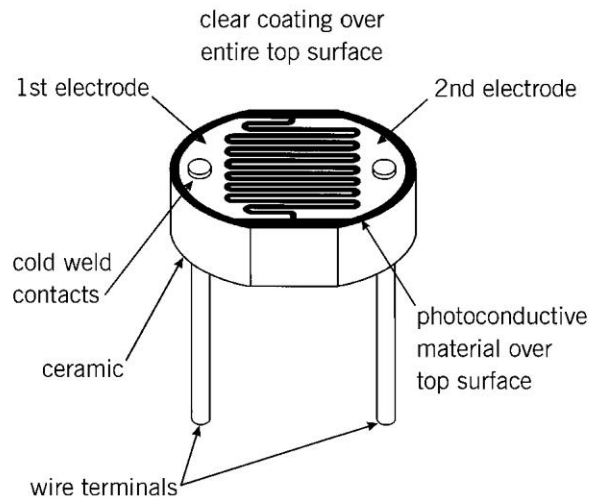
$W$  = width of the photoconductor



**NOTE:** In this figure, the electrodes are connected to the sides marked “L”; therefore “W” is the effective ‘width’ of the photoconductor.

The photoconductor we will be using in lab has a quite different “snake-like” geometry, used to control the resistance:

Photocells are thin film devices made by depositing a layer of a photoconductive material on a ceramic substrate. Metal contacts are evaporated over the surface of the photoconductor and external electrical connection is made to these contacts. These thin films of photoconductive material have a high sheet resistance. Therefore, the space between the two contacts is made narrow and interdigitated for low cell resistance at moderate light levels. This construction is shown in Figure 3.



**Figure 3**  
**Typical Construction of a Plastic Coated Photocell**  
 (from the article “Photoconductive Cells”)

To understand the reason for this, we re-write the equation for resistance in a slightly different form:

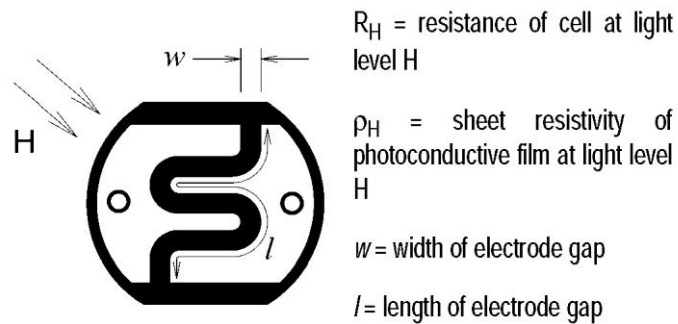
$$R_d = \frac{\rho W}{t L}$$

by replacing  $\frac{1}{\sigma}$  with the resistivity  $\rho$ . If we now define the ratio  $\frac{\rho}{t}$  as the “sheet resistance”  $R_s$ , then we can re-write the detector resistance as:

$$R_d = R_s \frac{W}{L}$$

The sheet resistance for a thin-film photoconductor is extremely high. To decrease the value of resistance for practical levels of illumination, the ratio  $\frac{W}{L}$  is made very small, leading to the thin “snake-like” geometry of these detectors.

The following figure from “Photoconductive Cells” further explains this geometry:



$R_H$  = resistance of cell at light level H

$\rho_H$  = sheet resistivity of photoconductive film at light level H

$w$  = width of electrode gap

$l$  = length of electrode gap

Sheet sensitivity ( $\rho_H$ ) for photoconductive films at 2 fc are in the range of 20 M $\Omega$  per square.

The ratio  $w / l$  can be varied over a wide range in order to achieve design goals. Typical values for  $w / l$  run from 0.002 to 0.5, providing flexibility for terminal resistance and maximum cell voltage.

## Lab Exercises:

### Part A. Resistance vs. Illumination—Qualitative

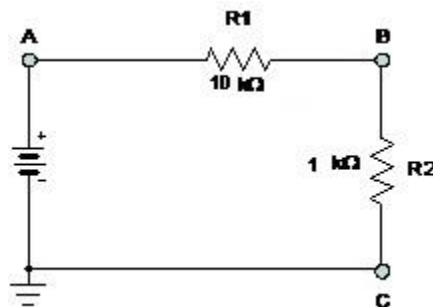
[20 min.]

- Using the breadboard, connect the photoconductor detector to the DMM, using a BNC cable.
- Illuminate the photoconductor detector with the table lamp. Vary the amount of light falling on the detector.
  - [Q1] How does the resistance vary with light level?
- Cover the detector with black cloth, placing it in complete darkness.
  - [Q2] What is the “dark” resistance?
- You will observe that the “dark” resistance is too high to be measured with the DMM! Remove the BNC cable from the DMM, and connect it to the input of the Agilent 34401 Multimeter. Again, measure (or try to measure) the “dark” resistance.
  - [Q3] What is the “dark” resistance measured with the Agilent 34401?

### Part B. Resistive Voltage Divider— $R_1$ and $R_2$

[30 min.]

- Using the breadboard, build the following series circuit ( $R_1 = 10\text{k}\Omega$ ) and ( $R_2 = 1\text{k}\Omega$ ):



Note that the voltage is supplied by the power supply (not a battery as shown in the schematic drawing). In this circuit,  $R_2$  simulates the photoconductor detector, and  $R_1$  is the “load” resistor, used to limit the current through  $R_2$ .

Our goal is to measure the IV curve of  $R_2$ :

- First, use the HP34401 Multimeter to (accurately) measure the value of  $R_1$ .
  - [Q4] Record the value of  $R_1$ .

7. Connect the Agilent 34401 Multimeter across points A and B. Note the proper polarities of the connections you make: point “A” is the Red input to the Multimeter, and point “B” is the Black (ground) input to the Multimeter.

This will measure the voltage drop across R1. In turn, use this value of voltage to calculate I, the current flowing through the circuit:

$$V_{AB} = I \cdot R_1 \quad ; \quad I = \frac{V_{AB}}{R_1}$$

The voltage drop across resistor R2 is simply given as:

$$V_{BC} = V_{AC} - V_{AB}$$

where  $V_{AC}$  is the voltage measured using the meter on the power supply itself.

8. Vary the voltage of the power supply from 0 to +10V in steps of 1V. At each voltage, record the value of  $V_{AB}$ .
9. Vary the voltage of the power supply from 0 to -10V in steps of -1V. At each voltage, record the value of  $V_{AB}$ .

**\*\*\* To supply negative voltages, simply reverse the Red/Black connections at the power supply.**

10. Use your data to calculate I and  $V_{BC} (\equiv V_2)$ , the current through resistor  $R_2$  as a function of the voltage across  $R_2$ .
  - [Q5] Use Excel to make a plot of I vs.  $V_2$ .
11. Use the “Add Trendline /Linear” option to curve-fit to your data.
  - [Q6] Use the value of slope to calculate the resistance of  $R_2$ .
12. Use the Agilent 34401 Multimeter to (accurately) measure the value of  $R_2$ .
  - [Q7] Compare the 2 values for  $R_2$  (measured directly and calculated from the IV curve).

**Part C. Resistive Voltage Divider— $R_1$  and  $R_{PC}$**

[30 min.]

\*\*\* Repeat the steps in Part B to measure the IV Curve of the photoconductor, under 3 values of illumination.

**Part D. Resistance vs. Illumination—Quantitative**

[45 min.]

Using the setup provided, measure the resistance of the detector as a function of the amount of light falling on it. Because we aren't using an optical power meter to measure the actual amount of light (in watts), we will "normalize" our measurements to the greatest amount of light from our source:

13. Study the setup provided. The rail carrier with the 2 post holders allows you to place either 1 or 2 ND filters into the optical path.

- [Q8] What two "optical" things could you do to increase the amount of light on the detector (not using any ND filters....all they do is decrease the amount of light!)

14. For each of the following values of ND, measure the resistance of the photoconductor:

<u>ND</u>	<u>ND</u>	<u>ND</u>
0 ("full" illumination)	1.0	3.0
0.1	1.2	4
0.2	1.3	
0.3	1.5	
0.4	2.0	
0.5	2.5	
0.2 + 0.3	1.0 + 1.5	

- [Q9] According to theory, values of ND add. So, according to theory, the resistance you measured for illumination level (ND = 0.2) + (ND = 0.3) should be the same as for illumination level (ND = 0.5). Was this true? .....  
..... Probably not. Why not? What could account for the difference?



15. Use Excel to plot resistance (in  $k\Omega$ ) vs. “Normalized Amount of Light” on the detector.

HINT: “Normalized Amount of Light” will be a scale going from 0 to 1 on the x-axis. In other words, this is the transmission value T of the ND filters:

<u>ND</u>	<u>T</u>	<u>Amount of Light</u>
$\infty$	0	NONE (complete darkness)
...	...	...
2	0.01	1%
...	...	...
1.0	0.1	10%
...	...	...
0.3	0.501	50.1%
...	...	...
0	1	100%

16. Use the “Add Trendline / Power” option to curve-fit to your data.

- [Q10] What equation best-fits your data? Does this match the theoretical equation? Explain!

**Part E. Measure W/L**

*[10 min.]*

Using the microscope on the translation stage:

- [Q11] Make a drawing of the photoconductor. Label W and L on your drawing.
17. Measure W.
18. Measure L (really an estimate, no need to take into account the curved ends of the “snake”).
- [Q12] Calculate (estimate) the ratio W/L.