

OPTI 202L – Lab 12

Photodiodes, Solar Cells, LED's, and Diode Lasers

Learning Objectives

Learn:

- (something) about photodiodes, solar cells, LED's, and Diode Lasers!

Useful Reading:

- Review your class notes on photoconductors from OPTI 240.
- Optical Radiation Detectors, Ch. 3, Dereniak and Crowe, 1984.

Theory:

(The following is taken from Optical Radiation Detectors, Ch. 3, Dereniak and Crowe, 1984):

Intrinsic Photovoltaic Effect

“The photovoltaic effect requires a potential barrier with an electric field in order to operate. A semiconductor P - N junction is usually employed to obtain these conditions. The following Figure 12-1 illustrates the energy-band diagram of a P - N junction. An incident photon of energy greater than or equal to the energy gap E_g can create a hole-electron pair, as shown in the figure. The electric field of the junction will not allow the hole-electron pair to recombine. The photoelectrons are therefore available to produce a current through an external circuit.

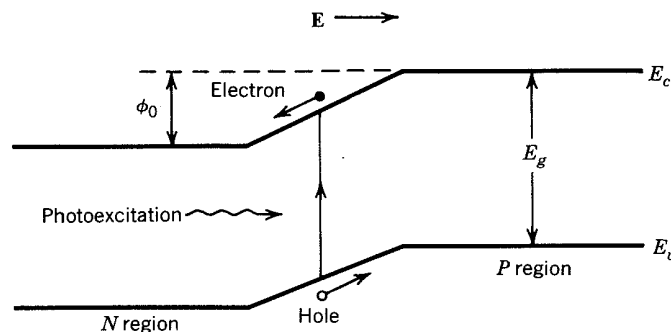


Figure 12-1

The photovoltaic effect, then, is the generation of a voltage difference by incident photons. The voltage arises because the P - N junction electric field forces photoelectrons to remain in the N region, and the corresponding holes produced by the photoexcitation are forced to occupy the P region. The maximum possible voltage produced in this way is labeled ϕ_0 , as shown in Figure 12-1. The actual voltage produced is a function of the load (resistor) that is connected to the photovoltaic device, and the properties of the semiconducting material used.

Two basic requirements for photovoltaic operation are that the incident photons have sufficient energy to excite photoelectrons across the energy gap and that the temperature of the detector be low enough so that the electrons are not thermally excited across the band gap. The photon restriction is

$$h\nu = \frac{hc}{\lambda} \geq E_g$$

where h = Planck's constant = 6.626×10^{-34} J sec
 ν = the optical radiation (light) frequency in Hz
 c = the speed of light = 2.998×10^{10} cm sec⁻¹
 λ = the optical radiation wavelength in cm
 E_g = the energy gap in J

This implies an upper limit to the wavelength at which the photovoltaic effect will operate:

$$\lambda_{\max} = \frac{1.24}{E_g}$$

where E_g = the junction energy gap in electron volts (eV)
 λ = wavelength in μm .

The thermal constraint is

$$\frac{kT}{q} \ll E_g$$

where $k = 1.38 \times 10^{-23}$ W sec K⁻¹ is Boltzmann's constant
 T = the temperature (K).

This ensures that electrons will be available for photoexcitation. The following table lists some values of E_g , λ_{\max} , and operating temperature for common photovoltaic devices."

Detector	E_g (eV)	T (typical operation) (K)	λ_{\max} (μm)
InSb	0.22	77	5.5
PbS	0.42	193	3
Ge	0.67	193	1.9
Si	1.12	300	1.1
CdSe	1.8	300	0.69
CdS	2.4	300	0.52

Photocurrent

The current characteristics of the P-N junction in the absence of light are summarized in the following Figure 12-2:

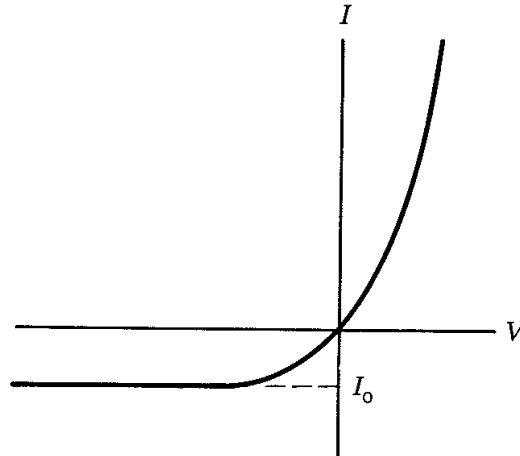


Figure 12-2

The dark current as a function of applied voltage is

$$I_{dark} = I_o \left[e^{qV/kT} - 1 \right]$$

where $q = 1.6 \times 10^{-19}$ C is the charge on an electron, and I_o is the reverse saturation current characteristic of the diode. The reverse saturation current is a strong function of temperature for a given junction. In silicon P-N junctions, for example, I_o approximately doubles for each temperature increase of 10 K.

Exposing the P-N junction to optical radiation shifts the $I(V)$ curve downward by an amount known as the photocurrent (photon-generated current), I_p . This shift is shown in Figure 12-3. The photocurrent is given by

$$I_p = \eta q E_e A_d \frac{\lambda}{hc}$$

where η = the quantum efficiency (the number of photoelectrons generated per incident photon)

E_e = the incident radiant flux density (irradiance) in W cm^{-2}

A_d = the area of the photovoltaic device (i.e. the photodiode detector)

c = the speed of light

h = Planck's constant = 6.626×10^{-34} W sec²

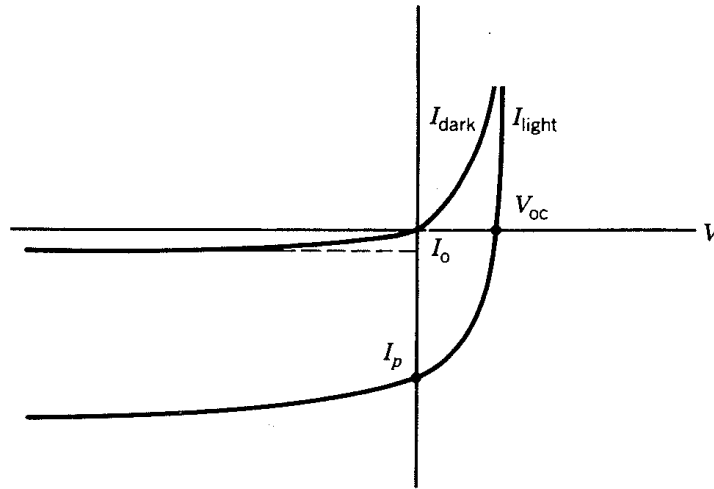


Figure 12-3

This short-circuit current is a linear function of incident flux typically over a range of 10^7 . The total current in the presence of light is therefore

$$I_{TOTAL} = I_{dark} - I_{light} = I_{dark} - I_p$$

$$I_{TOTAL} = I_o \left[e^{qV/kT} - 1 \right] - \left(\eta q E_e A_d \frac{\lambda}{hc} \right)$$

This section has introduced the photovoltaic device as a current generator, but it is also commonly used as a power generator (i.e. a solar cell). The short-circuit current delivered by the device is equal to the photocurrent:

$$I_{SC} = I_p = \eta q E_e A_d \frac{\lambda}{hc}$$

The open-circuit voltage is:

$$V_{OC} = \frac{kT}{q} \ln \left[\frac{I_p + I_o}{I_o} \right]$$

NOTE: This equation is found by setting $I_{TOTAL} = 0$ and solving for $V \equiv V_{OC}$:

Derivation of the equation for V_{OC} :

$$I_{TOTAL} = I_o [e^{qV/kT} - 1] - I_p$$

$$0 = I_o [e^{qV_{OC}/kT} - 1] - I_p$$

$$\frac{I_p}{I_o} = e^{qV_{OC}/kT} - 1$$

$$\frac{I_p}{I_o} + 1 = e^{qV_{OC}/kT}$$

$$\ln(e^{qV_{OC}/kT}) = \ln\left[\frac{I_p + I_o}{I_o}\right]$$

$$qV_{OC}/kT = \ln\left[\frac{I_p + I_o}{I_o}\right]$$

$$\therefore V_{OC} = \frac{kT}{q} \ln\left[\frac{I_p + I_o}{I_o}\right]$$

Note that at 25°C (room temperature), $\frac{kT}{q} \approx 0.0259$ Volts

Solar cells can provide power by operating into a finite load resistance R_L as shown in Figure 12-4. This results in power generated, represented by the shaded area in the figure. This power is the product of (some) VI , where $0 < V < V_{OC}$, and $0 < I < I_p$.

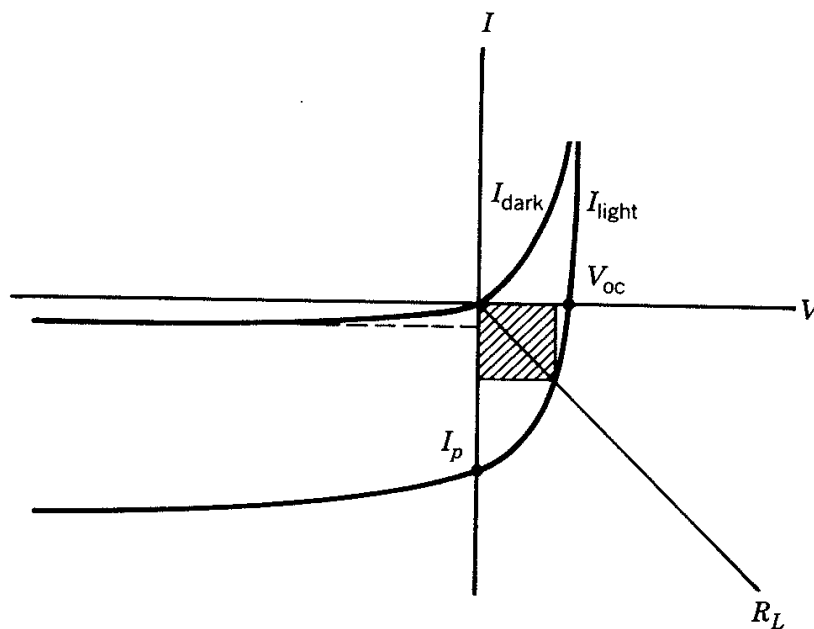


Figure 12-4

Lab Exercises:

Part A. IV Curve of a 1N914 Diode

[45 min.]

Measure IV (Reverse-direction):

1. Using the breadboard, connect the 1N914 small-signal silicon diode in series with a $1\text{k}\Omega$ resistor and the power supply. Connect the diode having reverse polarity, with respect to the power supply.
2. Set the power supply to 10V (-10V across the diode). Use the HP 34401 Multimeter to measure the voltage V_R across the $1\text{ k}\Omega$ resistor, and the voltage V_{TOT} across the complete circuit (i.e. the voltage of the power supply).
- [Q1] Using these two voltage measurements, calculate I_{diode} and V_{diode} .
3. Repeat step 2 for $V = 9, 8, 7, 6, 5, 4, 3, 2, 1,$ and 0 volts.

Measure IV (Forward-direction):

Because the IV curve rises so quickly in the forward-direction, we need to either:

- make very small changes in V and measure I , or
- make very small changes in I and measure V !

Because our ability to set the power supply voltage in very small increments is terrible, we will use the Diode Laser Current Sources to supply a constant current through the diode, and then use our high-precision HP 34401 Multimeter to measure the voltage across the diode.

- [Q2] Explain the difference between using the power supply and the current source.
4. Disconnect the power supply and remove the $1\text{ k}\Omega$ resistor from the circuit.
 5. Connect the current source to just the 1N914 diode. (Use jumper wires and the alligator clip leads to do this...kinda “kludgy, but welcome to the world of electronic breadboarding).

If you are using the ILX “LDC-3525”:

- connect pins 1 & 2 together (enables the interlock)
- connect the anode of the diode to pin 8
- connect the cathode of the diode to pin 4

If you are using the ThorLabs “LDC 202 C”:

- connect pins 1 & 5 together (enables the interlock)
- connect the anode of the diode to pin 8
- connect the cathode of the diode to pin 3

6. Connect the HP 34401 Multimeter across the diode, and set it to measure DCV.
7. Adjust the current from 0 to 50 mA, in appropriately-small steps and measure the voltage across the diode (for each current setting).
8. Use Excel to plot the IV curve of the 1N914 diode.

Part B. IV Curve of a Photodiode

[45 min.]

9. Repeat Part A using the photodiode:
 - in the dark.
 - with a constant amount of light on it.

Part C. Solar Cell— V_{OC} and I_{SC} vs. Light

[10 min.]

10. Use the hand-held DMM to measure the open-circuit voltage V_{OC} and the short-circuit current I_{SC} of the solar cell, in full sunlight.

Part D. Solar Cell—Power

[10 min.]

- [Q3] Using your measurements of V_{OC} and I_{SC} , calculate the maximum power that this cell is capable of producing.
- [Q4] Calculate the load resistance R_L needed to operate the cell at this “operating point” on the IV curve. Refer to Figure 12-4.

Part E. LED—Structure, L-I Curve, Spectral Output, V_F vs. λ_c

[30 min.]

Structure (use the setup provided, shared by everybody):

10. Use the microscope (and illuminator) to look at the LED chip, inside clear plastic housing.
 11. Slowly supply current to the LED until you begin to see it emit light!
- [Q5] Describe what you see.

L-I Curve (use the equipment at your individual table):

12. Mount the LED in the lens holder.
13. Position the detector of the ILX Optical Power Meter “close to” the LED.
14. Using the breadboard and alligator clip leads, connect the LED in series with a $1\text{k}\Omega$ resistor and the power supply. Connect the diode having forward polarity, with respect to the power supply.
15. Set the power supply to 10V, causing the LED to light up.
16. Adjust the heights of the LED and/or the Power Meter until you get maximum reading of the (relative) optical power from the LED. Cover the LED and detector on the Power Meter with a black cloth (to block out all other room light. This power meter is very sensitive to background light!)
17. Set the power supply to 0V. Use the HP 34401 Multimeter to measure the voltage V_R across the $1\text{ k}\Omega$ resistor.
 - **[Q6]** Using this voltage measurement, calculate I_{LED} .
18. Repeat for $V = 1,2,3,4,5,6,7,8,9$, and 10 volts.
19. Use Excel to plot an “L-I” curve for the LED (a plot of the light output vs. current through the LED).

Spectral Output and V_F vs. λ_c

20. Use the setup provided to measure the spectral output and the forward voltage drop for each of the provided LED's.

For each LED:

- set the current to 20 mA
- measure the voltage across the LED
- use the fiber optic-coupled spectrometer to measure the center wavelength, λ_c
- estimate the bandwidth (at FWHM) in nm

Part F . Diode Laser—Structure, L-I Curve

[30 min.]

21. Position the detector of the ILX Optical Power Meter “close to” the Diode Laser.
 22. Set the current source to around 20mA, causing the Diode Laser to light up.
 23. Adjust the heights of the Diode Laser and/or the Power Meter until you get maximum reading of the (relative) optical power from the Diode Laser. Cover the Diode Laser and detector on the Power Meter with a black cloth.
 24. Adjust the current source from 0 to 20 mA, in steps of 2 mA. For each current setting, record the (relative) optical power from the Diode Laser.
 25. Adjust the current source from 20 to 50 mA, in steps of 5 mA. For each current setting, record the (relative) optical power from the Diode Laser.
 26. Use Excel to plot an “L-I” curve for the Diode Laser (a plot of the light output vs. current through the laser junction).
- **[Q7]** On your L-I plot, mark the region of spontaneous emission, and of stimulated emission from the Diode Laser.
 - **[Q8]** Using your L-I plot, calculate the threshold current. Do this by extending the high-slope region (where stimulated emission occurs) backwards to the $I=0$ axis.
 - **[Q9]** Using your L-I plot, calculate the slope efficiency of this particular Diode Laser. The slope efficiency is defined, literally, as the slope of the L-I curve past threshold, with units of watts/amp.