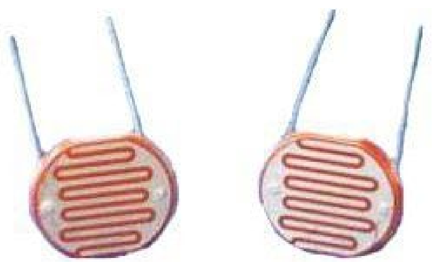
ECE 3040
Dr. Doolittle

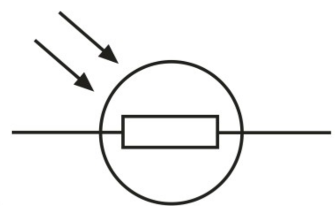
Homework 3

Unless otherwise specified, assume room temperature (T = 300K).

The goal of this homework is to design a light-dependent resistor (LDR), also known as a photoresistor or photocell. An LDR is simply a segment of semiconductor material used as a resistor with a resistance that is a function of illumination. CdS and CdSe are the most common semiconductors used for this application, due to bandgaps that are well-matched to visible and near-infrared wavelengths, respectively. The semiconductor is typically arranged in a long, winding pattern, but for this assignment, simply design the LDR to be one rectangular block.



Two light-dependent resistors



The circuit schematic of a light-dependent resistor

Given:
The LDR is made from CdS, designed to respond to visible light.
The bandgap of CdS is 2.42 eV.
The intrinsic carrier concentration of CdS is 10^3 cm^{-3}.
The semiconductor is n-type with an electron concentration of $5*10^{14}$ cm^{-3}
The electron mobility is 300 cm^2/V-s, and the hole mobility is 10 cm^2/V-s.

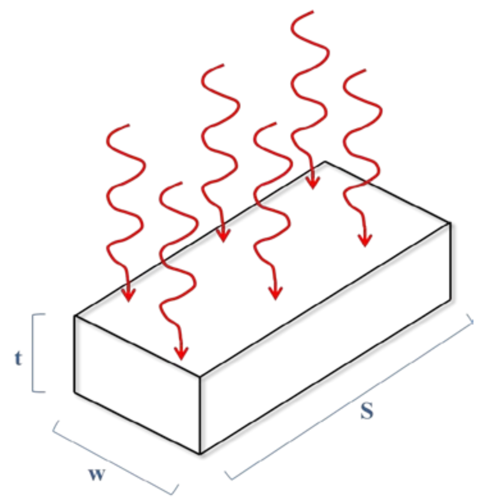
For this assignment it is okay to assume low-level injection for all parts, thus it is valid to use the following formula (Equation 3.34a in Section 3.3.3 of Pierret):

$$\left.\frac{\partial p}{\partial t}\right|_{\substack{\text{i-thermal}\\ \text{R-G}}} = -\frac{\Delta p}{\tau_p}$$

Although, in reality, we would be encountering high-level injection to achieve the amount of variation in resistance we are aiming for, and the use of the more general form would be necessary (Eq. 3.35):

$$\left.\frac{\partial p}{\partial t}\right|_{\substack{\text{i-thermal}\\ \text{R-G}}} = \left.\frac{\partial n}{\partial t}\right|_{\substack{\text{i-thermal}\\ \text{R-G}}} = \frac{n_i^2 - np}{\tau_p(n + n_1) + \tau_n(p + p_1)}$$

1) Purpose: Understanding the relationships between resistance, resistivity, and geometric dimensions of a semiconductor.
It is determined that the CdS film has a width, *w*, of 0.2 mm and a thickness, *t*, of 4 μm. What is the needed length, *S*, to achieve 50 MΩ resistance in the dark? See figure below for reference.
Note: Assume ohmic contacts are applied to both small faces of the bar (the *t* x *w* faces), so that carriers will flow along length *S*.



2) Purpose: Understanding generation of electron-hole pairs due to light.
Assume that the only recombination/generation mechanism possible in the semiconductor bar is band-to-band. In addition, assume there is uniform absorption and generation throughout the entire thickness of the film, and the absorption efficiency of the bar is 100% (all eligible incident photons are converted into electron-hole pairs in the semiconductor).

a. If the intensity of the incident light is 2 $\mu W/cm^2$ and the wavelengths of the incident photons are 600 nm, calculate the generation rate of electron-hole pairs in the semiconductor, G_L.
b. If the intensity of the incident light is .5 $\mu W/cm^2$ and the wavelengths of the incident photons are 512 nm, calculate the generation rate of electron-hole pairs in the semiconductor, G_L.
c. If the intensity of the incident light is 2.5 W/cm^2 and the wavelengths of the incident photons are 512 nm, calculate the generation rate of electron-hole pairs in the semiconductor, G_L.

Hint: The photon flux (number of photons per unit area per unit time) of the incident light can be obtained from the intensity of the light (total energy per unit area per unit time) and the energy of the individual photons. The generation rate is defined as the number of electron-hole pairs generated per unit volume per unit time, which is directly related to the photon flux. Be careful with unit conversions.

3) Purpose: Getting familiar with various levels of carrier injection.
If the minority carrier lifetime in the semiconductor is $2x10^{-6}$ s, what is the resistance of the semiconductor when it is illuminated with the following intensities? Assume the incident photons have a wavelength of 512 nm
   a. Intensity is 0.5 $\mu W/cm^2$
   b. Intensity is 2.5 W/cm^2.
Hint: Your answers for questions 2(b) and 2(c) should come in very handy here.

4) Purpose: Understanding Quasi-Fermi levels.
Assume that the intrinsic Fermi level lies exactly at midgap and the minority carrier lifetime is $2x10^{-6}$ s. Calculate and sketch the Fermi and/or Quasi-Fermi levels of the CdSe in the following conditions:
   a. In the dark.
   b. Illuminated with 0.5 $\mu W/cm^2$ and photons with wavelength of 512 nm.
   c. Illuminated with 2.5 W/cm^2 and photons with wavelength of 512 nm.

5) Purpose: Understanding electron and hole drift current.
If 50 V DC is applied across the length of the LDR in various stages of its illumination, what will the electron and hole currents be? Continue to assume the minority carrier lifetime is $2x10^{-6}$ cm^2/V-s.
   a. In the dark.
   b. Illuminated with 0.5 $\mu W/cm^2$ and photons with wavelength of 512 nm.
   c. Illuminated with 2.5 W/cm^2 and photons with wavelength of 512 nm.

6) Purpose: Understanding minority carrier concentration transients.
Consider the case where the CdSe is illuminated with an intensity of 1 $\mu W/cm^2$ for a very long time, and the light is suddenly turned off at time $t = 0$ s. Sketch and label the hole concentration as a function of time. Denote the hole concentration at time $t = 0$ s, after 3 minority carrier lifetimes have passed, and after 5 minority carrier lifetimes have passed. Assume the photons have a wavelength of 712 nm.

Given:
The LDR is made from CdSe, designed to respond to near-infrared radiation. The bandgap of CdSe is 1.74 eV.

The intrinsic carrier concentration of CdSe is 8000 cm^{-3}.

The semiconductor is n-type with an electron concentration of 10^{13} cm^{-3}.

The electron mobility is 500 cm^2/V-s, and the hole mobility is 10 cm^2/V-s.

CdSe thickness, t is 5 μm and minority carrier lifetime in the semiconductor is $5x10^{-6}$ s