DREXEL UNIVERSITY
Electrical and Computer Engineering
College of Engineering

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Electrical and Computer Engineering Dept.
Electronic Devices Laboratory, ECE-370

TITLE: **Semiconductor Optics**

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SECTION: **061**

DATE PERFORMED: **4/15/2022**

DATE DUE: **4/22/2022**

Objective

This lab consisted of looking into the effect of light into semiconductors. From this, arose the discussion of how exactly light can change the semiconductor conductivity and produce excess charge carriers past equilibrium. Photoconductors are a prime example of a semiconductor in which excess charge carriers determine its conductivity. This lab will explore the physics behind photoconductors and what is 'sensitivity' with respect to photoconductors.

As we go deeper into the physics behind impingement of light on semiconductors, questions such as, what is the dependence of conductivity on generation rate as well as carrier lifetime. In order to make a statement on the dependence between carrier lifetime and conductivity, it is necessary to determine the carrier lifetime.

Theory

One of the first questions which needs to be answered is how can light change semiconductor conductivity? This all comes down to the creation of Electron-Hole Pairs (EHP), when a photon gives the electron enough energy to break its covalent bond in the conduction band and move to the valence band. At equilibrium, or when there is no externally applied bias, there is a set number of holes and electrons. When adequate light is shown onto the semiconductor, there will be an increase in the charge carrier count show in:

Equation 1: $$\Delta\sigma = q(\delta n \mu_n + \delta p \mu_p)$$

The n and p refer to the excess charge carriers created, thus there will be a change in conductivity when there is an increase in charge carriers. The following figure will give more graphical intuition into exactly what is going on at an atomic level:

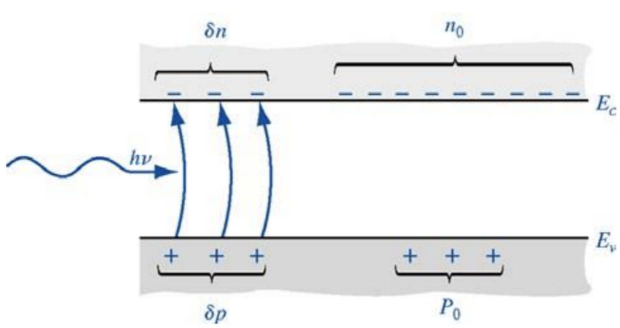


Figure 1. Carrier δn= δp produced by light in excess of equilibrium carriers n_0 and p_0.

Another question that must be explored is what exactly are the operations of photoconductors and what is meant when speaking about a photoconductor's sensitivity? As mentioned earlier, the operation of photoconductors occurs when there is an optic bias placed on the semiconductor. The rate of carrier charge creations is dependent on the intensity of light. The following equation will show how a higher charge creation rate will increase the conductivity:

$$\Delta\sigma = qg'\left(\tau_n \mu_n + \tau_p \mu_p\right).$$

Equation 2:

Now that there is a higher conductivity there will be a higher current in the photoconductive circuit. Sensitivity is the ratio of current in the photoconductive circuit to the current used to produce the intensity of light. As the current going into the light increases so does the intensity so the photoconductive current will increase yielding a mostly constant sensitivity.

Delving deeper into the relationships of carriers with conductivity, the effect of rate of charge carrier creations and carrier lifetime dependency is shown in equation 2. In equation 2, the terms written as tau are the lifetime of the charge carriers. For both of these variables, if they increase there will be an increase in conductivity.

In order to verify the relationships, it will be necessary to experimentally find the lifetime value. To do so, an equation will be used:

$$V(t) = v_0 \exp\left(-\frac{t}{\tau}\right)$$

Equation 3:

To obtain the variables needed, a waveform generator will be used in order to ensure that the LED decays so that it is dim before applying a current again. A function of current vs. time will be produced from the scope. Using Ohm’s law it is possible to obtain the voltage which can then be plotted against the log of time. Then, the slope will be -1/τ or -t. This will then allow for the lifetime to be found.

- CDS has a higher voltage across the resistor with the higher energy green light whereas the photodiode has a higher voltage across resistor with the higher energy red light

Experiment Results

The graphs below depict the relationship between the circuit input current and the current across two different photoconductors (the photocurrent), CDS and Si Phototransistor. Additionally, the values were compared using both green and red Light Emitting Diodes. By having measured the voltage across the photoconductor via oscilloscope, the photocurrent was found using the relationship of Ohm's Law.

Equation 4: Vc = R*Id, the photocurrent (Id).

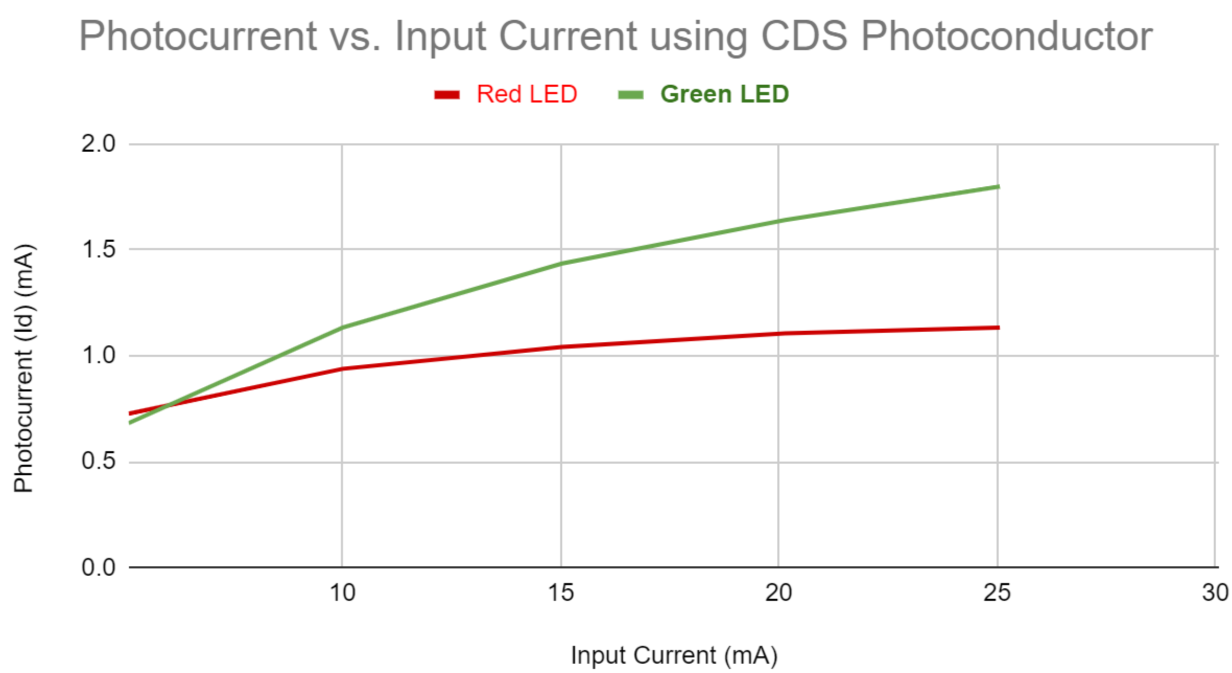

Photocurrent vs. Input Current using CDS Photoconductor
Red LED
Green LED
2.0
1.5
1.0
0.5
0.0
Photocurrent (Id) (mA)
10
15
20
25
30
Input Current (mA)

Fig 2

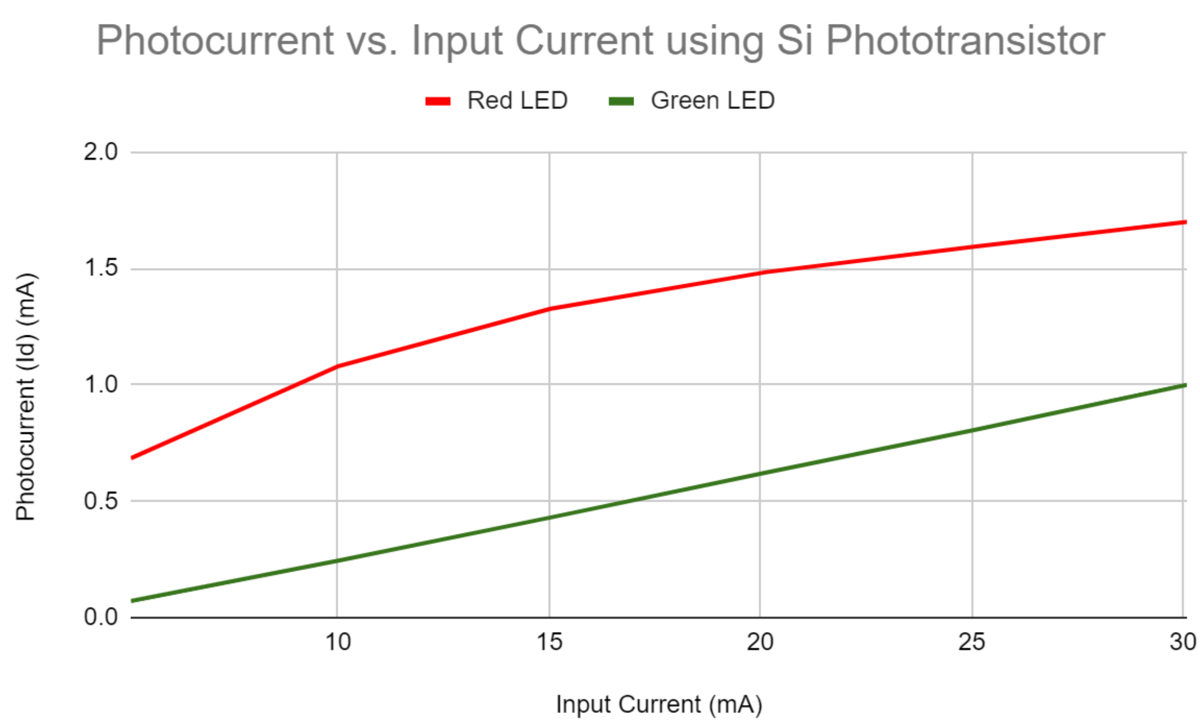

Photocurrent vs. Input Current using Si Phototransistor
Red LED
Green LED
2.0
1.5
1.0
0.5
0.0
Photocurrent (Id) (mA)
10
15
20
25
30
Input Current (mA)

Fig 3

It was then possible to verify the equations for the change in conductivity due to light using the graphical representation of the experiment.

Equation 5: $$\Delta\sigma = q\left(\delta n \mu_n + \delta p \mu_p\right)$$

Equation 6: $$\Delta\sigma = qg'\left(\tau_n \mu_n + \tau_p \mu_p\right).$$

Equations 5 and 6 mathematically show that conductivity increases with generation rate as light intensity increases through multiplication. This same relationship with the experimental data as photocurrent increases with input current.

Data Sheet & Calculations

Looking at Fig 2, the sensitivity of the CdS photoconductor can be determined by finding the slope of the graph. For the green diode, the sensitivity is 5.47*10^-5 whereas, with the red diode the sensitivity is 1.96*10^-5.

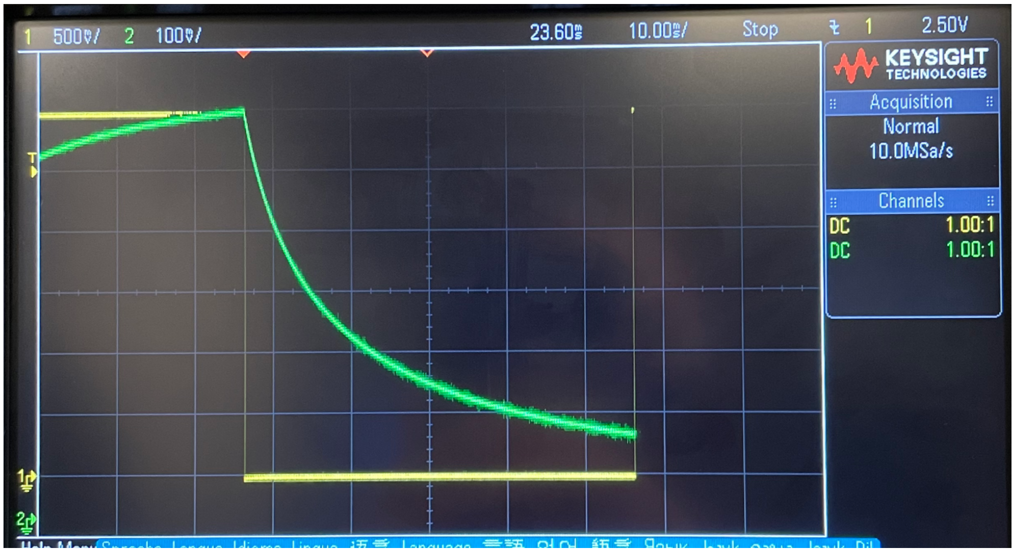
Looking at FIg 3, the sensitivity of the Si Phototransistor is determined the same way. For the red diode, the sensitivity is 3.87*10^-3, whereas, for the green diode the sensitivity is 3.72*10^-3.

From the values above, it is possible to conclude that the Si Phototransistor is more sensitive than the CdS photoconductor.

Lifetime of CdS

CdS was the semiconductor of choice to use as a photoconductor to measure the lifetime of the carrier charges. The following image shows the voltage vs. time plot for a periodic signal being sent to the LED to power it:

Figure 3:



The yellow line in Figure 3 refers to the state of the LED, with the higher of the two being on and the lower being off. In order to interpret this graph, equation 3 will need to be used, as it is for the relationship between voltage and time. Time 0 will be taken as the highest point of the green line before the exponential decay begins. Taking this equation 3 becomes : $V(0) \;=\; Vo$. The voltage over the resistor is the green line and it is in units of 100 mV/gap. Using the off state of the signal as y=0, it is possible to determine Vo. Vo is approximately 600 mV.

Now, it is necessary to find the width of time between one iteration of the lifetime. Using equation 3 once again $V(\tau) \;=\; Vo/e \;=\; 220.728\, mV$. With this in mind, it is now possible to find the location in which the voltage is equal to 220.728 mV. It follows that tau should be the space between the time coordinate where the voltage is 600 mV and 220.728 mV. This spacing is approximately 11 ms, as each x box is 10 ms. It is approximately one unit length away thus giving the indication that the lifetime is 10 ms.

The measurement of the lifetime semi-accurate. In this scenario, voltage is being used instead of the number of charge carriers created from the optical bias. While voltage is a somewhat good indicator, it would be much more accurate if the number of charge carriers were used. For instance, there are different lifetimes depending on if it is a hole or electron. The following equation will show the proper form:

Equation 7: $$\delta n(t) = \delta n(0)\exp\left(-\frac{t}{\tau_n}\right)$$

Equation 7 shows the proper equation. While voltage is influenced by charge carriers, at the end of the day it is in essence a variable dependent on the charge carriers, but also other variables that could be slightly skewed. Finally, due to the sheet number of carriers, using the number of charge carriers at various times would most likely yield a more accurate time constant.

LED photodiode configuration:

In the demonstration, we were shown how to configure a photodiode, using LEDs.As a photodiode, an LED is sensitive to wavelength equal to or shorter than the wavelength it emits.As more photons hit the photodiode the current increases causing a voltage across the diode.

From lab 1, it was concluded that a green LED has a wavelength of 555*10^-9 m and a bandgap energy of 3.581*10^-19 J. On the other hand, the red LED has a wavelength of 620*10^-9 m and a band gap energy of 3.206*10^-19 J.

Keeping the values above in mind, we can justify the demonstration. When the green led was the photodiode, it was sensitive to the red LED and changes were observed on the multimeter; however, there was less sensitivity noted when the red LED was used as the photodiode, as its wavelength is less than that of the green led.

Conclusion

To summarize this lab, photodiodes and photoconductors change the conductivity of the semiconductor when light is shone into them. This allows for current to move through the conductor when light is shone on it, because the conductivity increases. The increased conductivity occurs through the generation rate of charge carriers as well as lifetime due to equation 5 and 6.

One interesting point to note was the difference in sensitivity of CdS and Si. Si seems to have an equal sensitivity to both red and green light. This tells me that its bandgap isn't very low because green should be the more sensitive of the two as it delivers higher energy photons to the electrons in the covalent band.

Another interesting point in this lab is the calculation of the lifetime. The lifetime seems to be very difficult to calculate accurately as the original equation takes in the negative charge carriers from the optical bias. This would most likely require a lot of instrumentation, but using voltage over the resistor is a satisfactory replacement because it is heavily dependent on the conductance of the photodiode.

This lab helped initiate critical thinking on the applications of the photodiode, and how to use the knowledge from the previous lab and textbook to a new semiconductor concept. It also enhanced our knowledge on semiconductor properties as the demonstration with the LED as a photodiode shows the versatility of semiconductors.