Lab 7: Optical Absorption

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EE 145L
Section: Tuesday 9:00-11:00am

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1 Abstract

The purpose of this experiment is to characterize two semiconductor wafer samples (Silicon and Gallium Arsinide) in terms of their ability to transmit incident light at various wavelengths with the goal of experimentally determining their band-gap energy. The samples will also be experimentally characterized as direct or indirect band-gap semiconductors. It was found experimentally that the band-gap energy of Silicon is about 1.07eV and the band-gap energy of GaAs is about 1.36eV, compared to the theoretical values of 1.1eV and 1.43eV respectively at 300K. It was also demonstrated that Silicon is an indirect band-gap semiconductor, and that Gallium Arsinide is a direct bandgap semiconductor.

2 Introduction

When a material is exposed to light, that light may be transmitted through the material, absorbed by the material or reflected by the material. For a semiconductor, if the energy of an incident photon E_p is greater than the material's band-gap energy E_g, then the photon will be absorbed by the semiconductor, creating an EHP. In this lab, we will be exploring the absorption of light as a function of wavelength and photon energy by two semiconductor samples: A Si sample and a GaAs sample both of thickness $L = 0.5mm$.

Depending on the index of refraction of the semiconductor n, some of the light will be reflected. The portion of light reflected R is found by Equation 1, where $n = 3.874$ for Si at $\lambda \approx 1\mu m$ and $n = 3.59$ for GaAs at $\lambda \approx 1\mu m$. Given an incident light intensity of I_o, the intensity of the light that makes it through the reflective barrier is then $I_o(1-R)$. In the case of the wafer samples there are two such barriers (either side of the wafer), so the intensity of transmitted light is instead $I_o(1-R)^2$.

$$R = \frac{(n-1)^2}{(n+1)^2} \tag{1}$$

On a macro scale, as light with incident intensity I_o traverses through the semiconductor, there is a probability that some of the photons making up the light will be high enough energy to be absorbed. The amount of light that is transmitted through an absorbing medium decays exponentially according to Equation 2 where L is the thickness of the sample and α is the optical absorption coefficient, which is a function of light wavelength. Accounting for absorption and reflection, the value we will be measuring, which is the intensity of light transmitted through the semiconductor can be found as Equation 3.

$$I(x = L) = I_o e^{-\alpha L} \tag{2}$$

$$I_t = I_o(1 - R)^2 e^{-\alpha L} \tag{3}$$

The transmissivity of a material can be defined by Equation 4. The theoretical maximum transmissivity for which there is not absorption is defined by Equation 5. T_{raw} which is what we'll be measuring is the ratio of the measure light power defined by Equation 6. A normalizing parameter S can then be defined by Equation 7. To normalize all of the transmissivity data such that the effects of light scattering are removed, $T_{normalized}$ can be defined by Equation 8. From this relation, we can solve for the optical absorption coefficient $\alpha(\lambda)$ as shown in Equation 9.

$$T(\lambda) = \frac{I_t(\lambda)}{I_o(\lambda)} \tag{4}$$

$$T_{theo,max} = (1 - R)^2 \tag{5}$$

$$T_{raw} = \frac{P_{withsample}(\lambda)}{P_{withoutsample}(\lambda)} \tag{6}$$

$$S = \frac{T_{rawmax}}{T_{Theo,max}} \tag{7}$$

$$T_{normalized} = \frac{T_{raw}(\lambda)}{S} = e^{-\alpha L} \tag{8}$$

$$\alpha(\lambda) = \frac{-ln(T_{normalized}(\lambda))}{L} \tag{9}$$

Gallium Arsinide, being a direct bandgap semiconductor has an optical absorption coefficient which depends on photon energy according to Equation 10. This means that GaAs's α is dependant on $\sqrt{E_p}$. Silicon, being an indirect bandgap semiconductor, has an optical absorption coefficient which depends on photon energy according to Equation **??** through Equation 13. This means that Silicon's α is dependant on E_p^2.

$$\alpha = K_d(E_p - E_g)^{1/2} \tag{10}$$

$$\alpha = K_{i,a}[E_p - (E_{phonon})]^2 + K_{i,e}[E_p - (E_g + E_{phonon})]^2 \ if \ E_p > E_g + E_{phonon} \tag{11}$$

$$\alpha = K_{i,a}[E_p - (E_g - E_{phonon})]^2 \ if \ E_g - E_{phonon} < E_p < E_g + E_{phonon} \tag{12}$$

$$\alpha = 0 \ if \ E_p < E_g - E_{phonon} \tag{13}$$

The purpose of this lab is to characterize the absorption of light by Silicon and Galium Arsinide. This will be done by finding their transmissivity as a function of light wavelength and photon energy as well as their optical absorption coefficients. The band-gap energies of the samples will also be estimated from the data.

3 Materials and Methods

Materials:
-Silicon Sample
-Gallium Arsinide Sample
-Monochromator
-Tungsten lamp source
-Lock in amplifier
-Light chopper
-Silicon photodiode

Methods:

The experimental setup for the absorption experiment is shown in Figure 1. The experiment was performed for us by the lab TA, because of the sensitive and expensive equipment involved. First, the experiment was run without a wafer sample to obtain a control power curve to which the sample curves will be compared. Once this data was taken, the Silicon wafer was placed in behind the aperture and another set of power data was taken. This time, the lab TA conducting the experiment pointed out the drop in intensity associated with the band-gap energy of the silicon. The silicon wafer was then replaced by the Galium Arsinide wafer, and a third set of power data was taken for that sample.

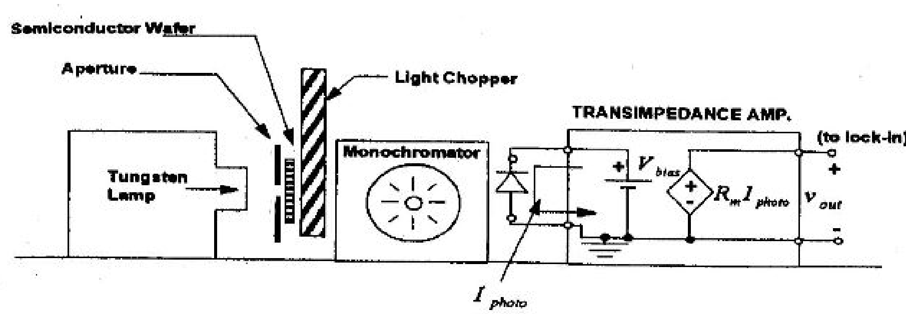

Figure 1: Setup for absorption experiment (credit to Lab 7 handout)

4 Results and Analysis

For a given wavelength of light, the photon energy of that light is equal to $E_p(eV) = \frac{1.24}{\lambda(\mu m)}$. From this, I calculated the photon energy from the light wavelength, shown on the x-axes of Figure 4 and Figure 5. Using Equation 1, R was found to be 0.348 for Silicon and 0.318 for GaAs. Using Equation 5, it was found that for Silicon, $T_{theo,max} = 0.425$ and for GaAs, $T_{theo,max} = 0.465$. These values were used to find S as $S = 0.305$ for Silicon and $S = 1.22$ for GeAs.

From some brief websearching, I found that the band-gap energy of Silicon at 300K is 1.1eV. This is reflected perfectly in the data. Referring to Figure 5, before 1.07 eV, the data is rough because the intensity of the incident light was relatively low. after 1.1eV, the normalized transmissivity begins to gradually drop off and by 1.25eV, the transmissivity is nearly zero, showing that all of the light was either absorbed or reflected by the material. From this data, I would estimate that the band-gap energy of Silicon is 1.07 eV, which is very close to the theoretical value. The reason the

Transmissivity drops off gradually rather than immediately is that the higher the average photon energy, the more likely it is that a high enough energy photon will collide with a valence electron, being absorbed.

Again from brief websearching, I found that the band-gap energy of GaAs is 1.43eV at 300K. Referring to Figure 4, the Transmissivity holds at around 0.45 with some slight drop off between 1.10eV and 1.35eV. Then, after 1.35eV the Transmissivity sharply drops off and becomes zero by 1.41eV. From this data, I would estimate that the band-gap energy of GaAs is 1.36eV because that's where the drop-off starts to occur, and therefore where photon absorbtion starts to largely occur. This is fairly close to the theoretical value of 1.43, but not as close as the results for Silicon.

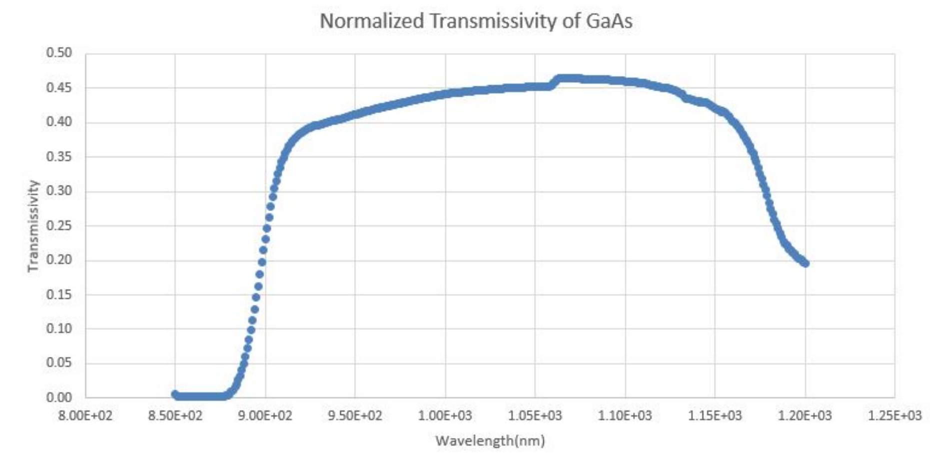

Figure 2: Normalized Transmissivity of Galium Arsinide vs Light Wavelength

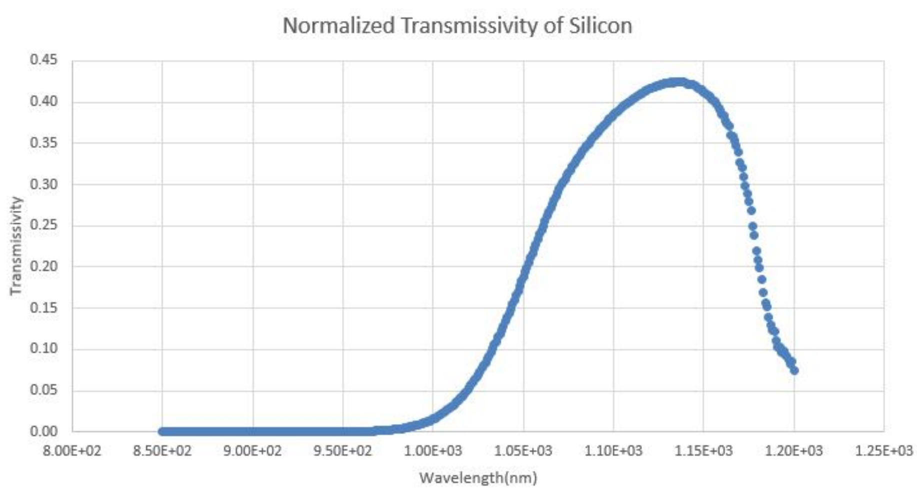

Figure 3: Normalized Transmissivity of Silicon vs Light Wavelength

Regarding the relationships of α to E_p, for GaAs which is a direct bandgap semiconductor, α should be linearly proportional to $\sqrt{E_p}$ according to Equation 10. This is shown in Figure 6 where I plotted α^2 against E_p to see if a linear relationship arose. It is difficult to see because of the sharpness of the transition of GaAs's transmissivity with respect to photon energy, but

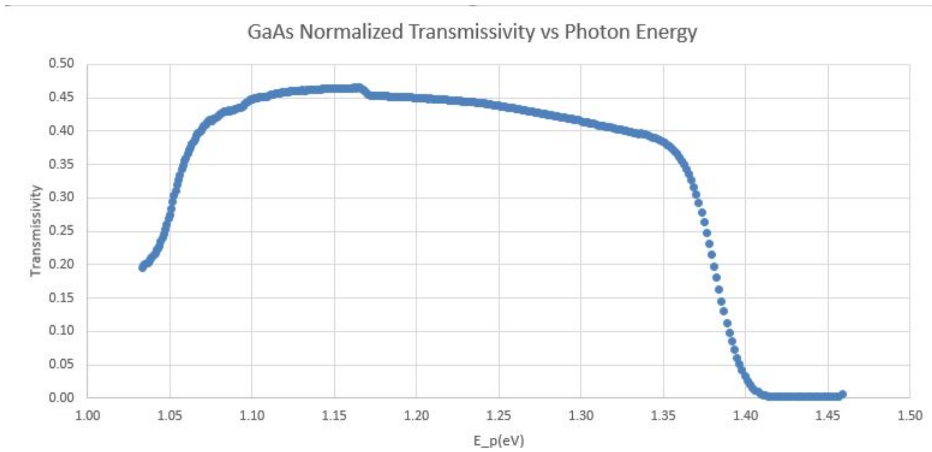

Figure 4: Normalized Transmissivity of Galium Arsinide vs Photon Energy

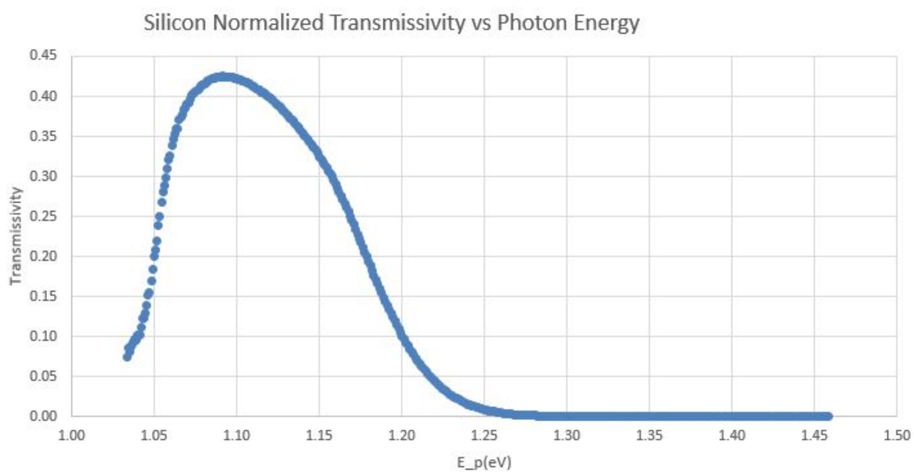

Figure 5: Normalized Transmissivity of Silicon vs Photon Energy

there is a range between 1.40eV and 1.41eV where there appears to be a linear relationship, which demonstrates that GaAs is a direct bandgap semiconductor.

The results for Silicon are much more obvious. Silicon, being an indirect bandgap should have an α linearly proportional to E_p^2. This is shown more obviously in Figure 7, where I have plotted $\sqrt{\alpha}$ against E_p. For the range of 1.20eV to about 1.29eV, an obvious linear relationship is shown, demonstrating that Silicon is an indirect bandgap semiconductor.

5 Conclusions

The results of this experiment were fair. The Transmissivity data showed with some accuracy the band-gap energy of the two samples. A result which was enlightening and which visually confirmed the theoretical concept of EHP creation via photoabsorption. The results for the optical absorption coefficient and determining whether a semiconductor was direct or indirect were a bit less clear and harder to parse. The α curves, for Gallium Arsinide especially, were a bit unclear as to in what range the relationship was supposed to be linear, although it was more obvious for Silicon. Overall,

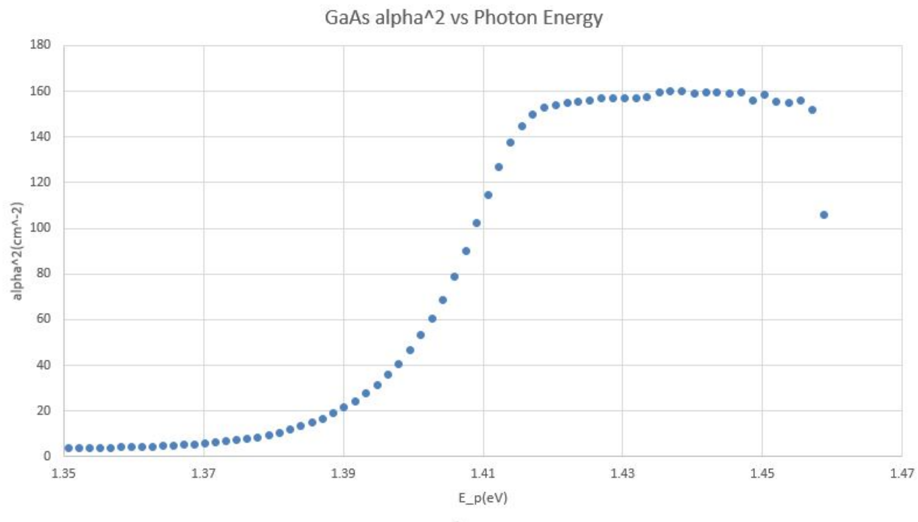

Figure 6: Showing linear relationship of α and $\sqrt{E_p}$ for Galium Arsenide, a direct bandgap semiconductor

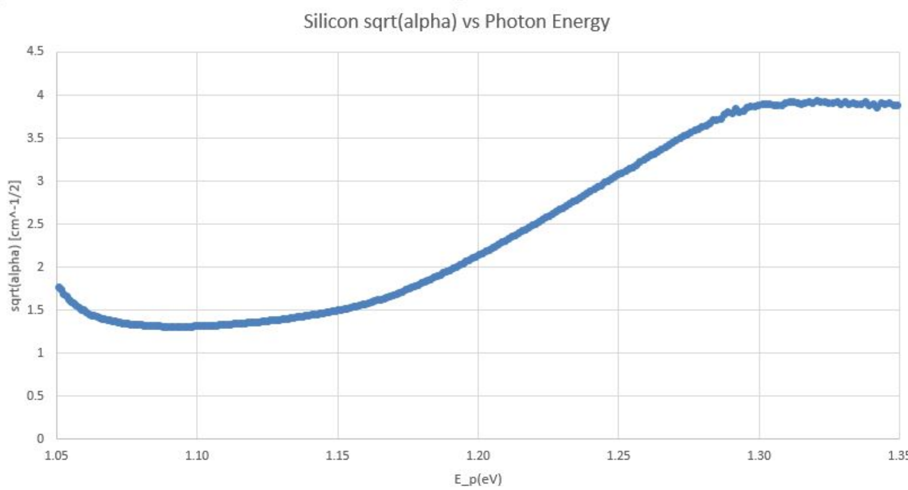

Figure 7: Showing linear relationship of α and E_p^2 for Silicon, an indirect bandgap semiconductor

an en-light-ening experiment.