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Formal Report

Investigation B

Optical Absorption of Semiconductors

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1 Abstract

In the optical absorption of semiconductor experiment, we discovered the Urbach slope, the band gap energy for both; direct and indirect band gap semiconductor. The experiment was carried out using Matlab to automate the wavelengths by outputting a signal through a stepper motor to the monochromator and analysing the data inputted back in through plotting graphs. The Urbach slope was found to be (0.182 ± 0.008) eV, the band gap energy for a direct band gap semiconductor to be (1.431 ± 0.002) eV and the band gap energy for an indirect band gap semiconductor to be (1.8305 ± 0.0146) eV.

2 Introduction

Semiconductor effect was first discovered by Michael Faraday while investigating the effects of temperature on silver sulphide in 1833. Then, at the beginning of the 20th century, the theory of electronic semi- conductors was published, as scientists were puzzled by a plausible explanation of semiconductor behaviour for decades. Since then, many developments in this area of Physics had made. [1]

A semiconductor is defined as a material which conducts electricity conditionally, hence, making it useful in controlling electrical current. It possesses intermediate conductivity, ranging between a conductor and an insulator. [2] Its conductance, defined as the ease of electrical current flowing through a substance, [3] is reliant on the applied current or voltage to a control electrode, or on the amount of irradiation by electromagnetic radiation. [4]

Semiconductors have a distinctive band structure; the fermi energy lies between the conduction and valence band in the band gap as shown in diagram 1 below. [5] The band gap is an important property of semiconductors, also known as forbidden energy band and electrons are absent in the band gap. [6] Quantitatively, it is defined as the minimum energy needed for an electron to shift from the valence band to the conduction band. [7] Band gap in semiconductors usually ranges between 1 and 4eV, less than the band gap in insulators, whilst more than the band gap in conductors. [8]

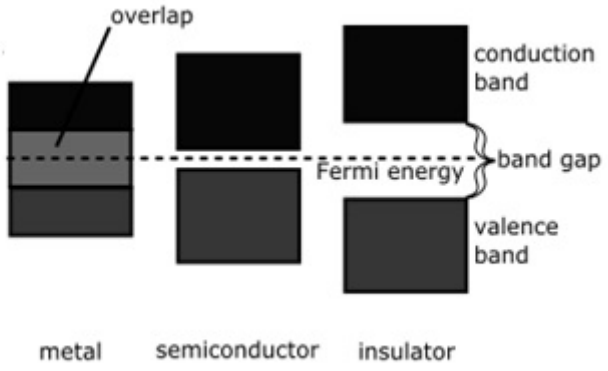


Diagram 1: This diagram shows the difference between the band gap of metal, semiconductor and insulator. [9]

Fermi energy is defined as the difference between the energy of the highest and lowest occupied single particle state, in a quantum system of non-interacting fermions at 0 K. [10] According to Pauli Exclusion principle, the electrons will fill all the available energy levels. The Fermi energy level is the maximum of that 'Fermi sea' of electrons. The Fermi energy level always lies halfway between the valence and the conduction band for a pure un-doped semiconductor at finite temperature. [11]

Fermi Dirac distribution describes the distribution of the electrons in the available energy levels.

$$f(\epsilon) = \frac{1}{e^{\frac{\epsilon-\mu}{k_B T}} + 1} \tag{1}$$

where $f(\epsilon)$ is the occupation probability of a state of energy , ϵ is the energy state, K_B is the Boltzmann's constant, μ is the chemical potential and T is the temperature in Kelvin.

In semiconductors, excited electrons move from the valence to the conduction band across the quantized energy range of the band gap due to the absorption of a photon or both, photon and phonon by quantum mechanical transitions. The band gap can be thermally populated with both electrons and holes as the Fermi energy level is near enough to both bands.

There are two different kinds of band gap in semiconductors: direct or indirect band

gap. A direct band gap is distinguished by having the band edges aligned in k, so that an electron can transit from the valence band to the conduction band. On the other hand, in the indirect band gap, the band edges are not aligned so the electron does not transit directly to the conduction band, both a photon and a phonon are involved. [8]

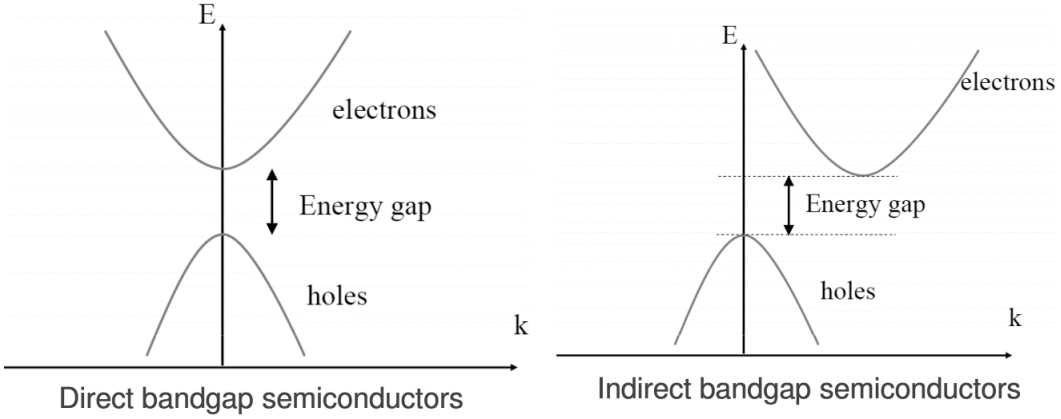


Diagram 2: This diagram shows the two different type of band gap: direct and indirect band gap with energy plotted against wave-vector. [12]

Semiconductors have had a colossal effect on our society. It is used in microprocessor chips, transistors, and even in solar cell. Also, majority of the devices that are electrical depends on semiconductors. [13] The most widely used semiconducting elements is silicon, much more than germanium because it can operate at much higher temperatures. [14] Hence, the term "Silicon Valley". Nanoscale semiconductors are generally the pillars of modern optoelectronic devices, an area that is being explored intensively. [15]

In this experiment, different quantities of direct and indirect band gap semiconductors are being using the apparatus and samples provided in conjunction with Matlab.

3 Theory

The absorption coefficient, α, is defined as a quantity that describes the ability of light of a particular wavelength to penetrate a material before being absorbed. The

absorption coefficient, α, of a semiconductor can be calculated from optical transmission data. These data are determined by measuring the intensity of a monochromatic light with wavelength λ, before, I_0 and after, I transmitting through a semiconducting wafer of thickness x. The transmission coefficient T, can be calculated through

$$T = \frac{I}{I_0} \tag{2}$$

Subsequently, after considering the numerous reflections that take place within the wafer, T can be determined by

$$T = \frac{(1-R)^2 exp(-\alpha x)}{1 - R^2 exp(-2\alpha x)} \tag{3}$$

where R is the reflection coefficient.

The imaginary part of a semiconductor's index of refraction,

$$k = \frac{\lambda \alpha}{4\pi} \tag{4}$$

is significantly smaller as opposed to the real part n in the region close to the band edge. As a result, the reflection coefficient becomes

$$R = (\frac{(n-1)}{n+1})^2 \tag{5}$$

In a semiconductor of band gap energy, E_g, the fundamental mechanism is the transitions of electrons from the valence to the conduction band.

The absorption coefficient of direct and indirect band gap are calculated differently. Applying the parabolic approximation, a photon of energy E directly creates an electron hole pair for a direct band gap in the region close to the band edge. As a result, the absorption coefficient is given by

$$\alpha = A(E - E_g)^{1/2} \tag{6}$$

where A is a constant that is dependent on properties of the material, E is the energy of the photon and E_g is the energy of the band gap.

Conversely, doping and temperature effects will lead to the extension of the exponential band- tails of electronic states into the forbidden gap of the semiconductor.

This band tail is known as the Urbach slope, a quantity describing the slope of the band tail. Therefore, the absorption coefficient will be given by

$$\alpha = Bexp(E/E_0) \tag{7}$$

where B is a constant that is dependent on properties of the material, E_0 is the Urbach slope.

Then, applying the parabolic approximation as in the previous case, the absorption coefficient of an indirect band gap semiconductor can be calculated using

$$\alpha = \alpha_a + \alpha_e \tag{8}$$

where α_a is the absorption coefficient due to transitions involving the absorption of a phonon and α_e is the absorption coefficient due to transitions involving the emission of a phonon.

The α_a and α_e can be calculated using

$$\alpha_a = C(E - E_g + E_p)^2, \; where\, E > E_g - E_p \tag{9}$$

$$\alpha_e = D(E - E_g - E_p)^2, \; where\, E > E_g + E_p \tag{10}$$

where E is the energy of the photon, E_g is the energy of the band gap, E_p is the energy of the phonon, C and D are constants that depend on material properties and temperature.

During the transitions involving the absorption of a phonon, an excited electron is created by a photon together with a thermally available phonon while both an excited electron and a phonon are created through the transitions involving the emission of a phonon. The latter process has a higher optical energy threshold.

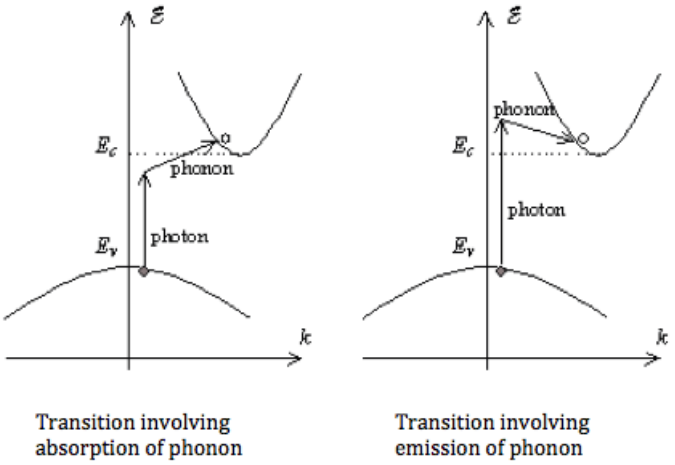


Diagram 3: This diagram shows the two different ways electrons can transition from the valence to the conduction band in an indirect band gap semiconductor. [17]

In this experiment, lock- in detection method was employed to determine the absorption coefficient, α, near the band edge. The analysis of the data obtained will lead to determination of the nature of the band gap, direct or indirect by extrapolating the straight line plots of $\alpha^{1/2}$ and α^2 against energy of phonon. For a direct band gap, band gap energy, E_g and the Urbach slope, E_0 will be determined. In the case of an indirect band gap, band gap energy E_g and the phonon energy involved, E_p will be calculated. [16]

4 Experimental Methods

The investigation on direct, and indirect band gap semiconductors will be carried out in this experiment.

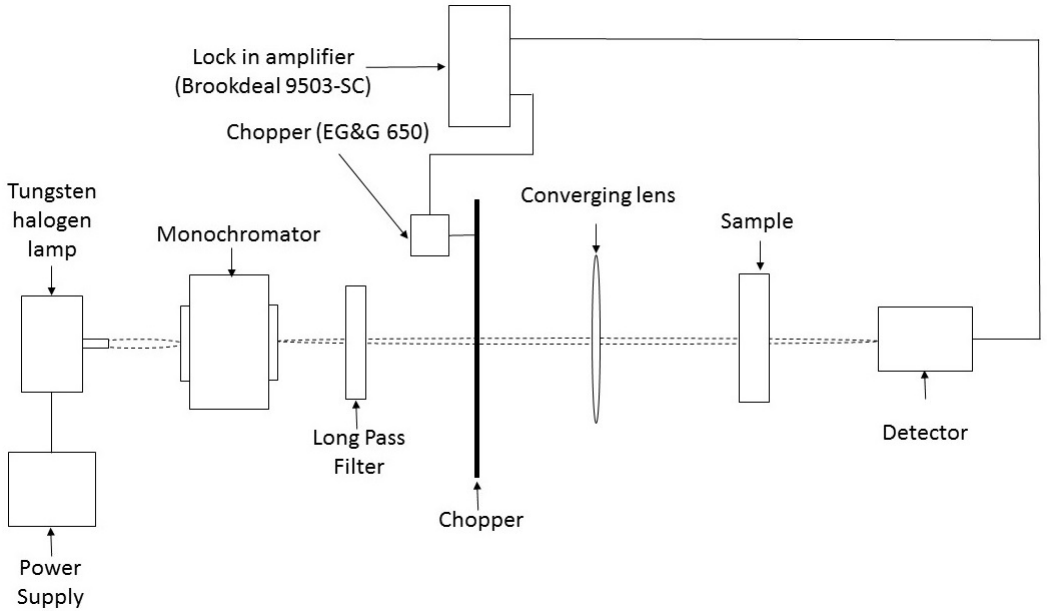


Diagram 4: Experimental set up with the apparatus mounted on a metal track.

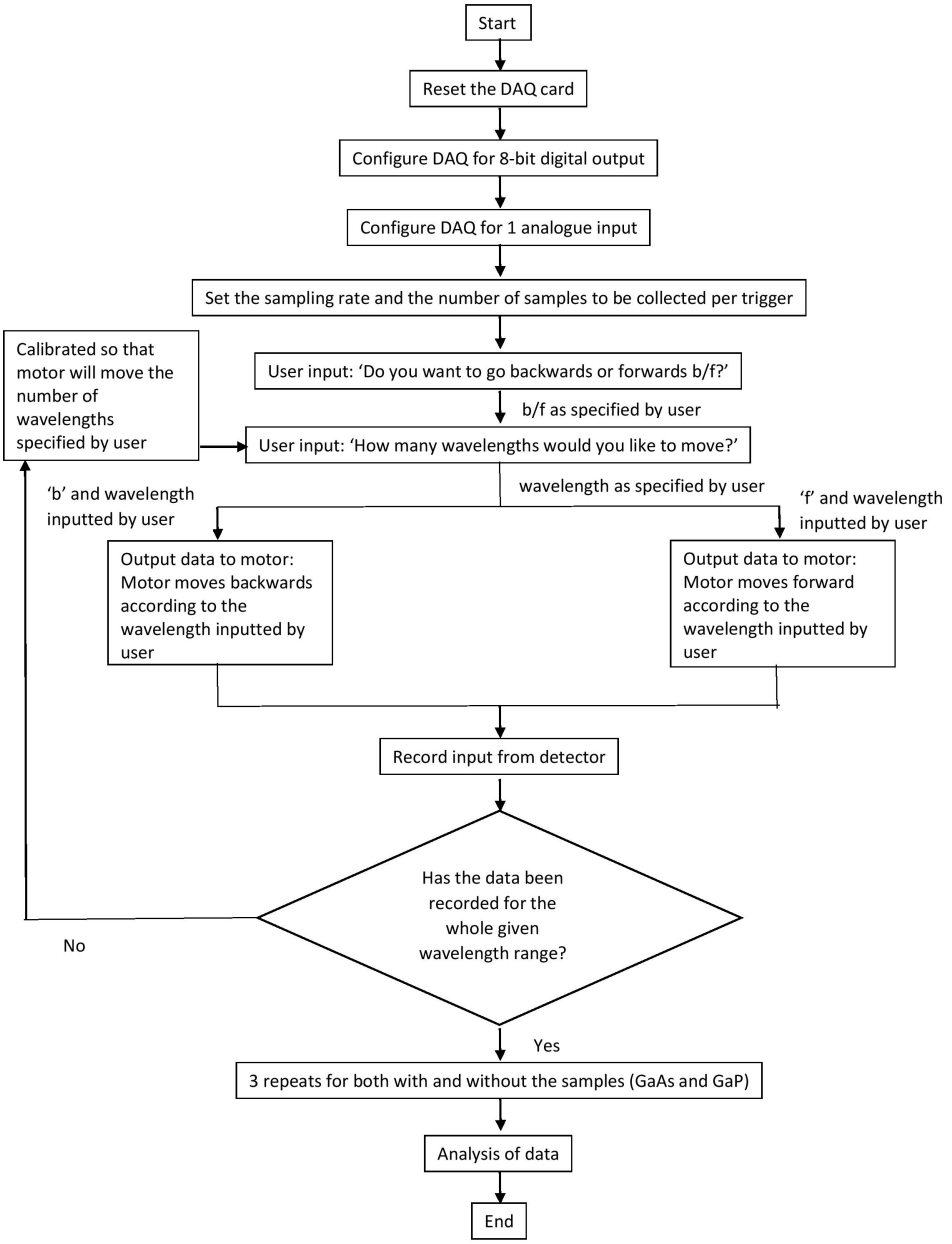
As there are two main parts in the experiment, investigation of direct, and indirect band gap semiconductors, Tungsten halogen lamps of 2 different power were used, 100W for GaAs, the direct band gap sample, and 20W for GaP, the indirect band gap sample. The monochromator has 600 line gratings and a 0.5mm exit slit. Although this monochromator was used for both samples, the Spex Minimate monochromator that has 1200 line gratings blazed at approximately 800nm with an unknown size exit hole would have been more suited for the GaAs sample, providing more accurate results. The long pass filter prevents getting ultraviolet and blue light from the 2nd order diffraction in the infrared part of the spectrum from the 1st order diffraction.

The chopping frequency was set to be a 4 digit prime number to prevent the formation of harmonics. Then, the apparatus were aligned to ensure the beam reaches the detector with the highest intensity achievable experimentally. The position of the set up was recorded and retained for the whole experiment as shifting the positions of the apparatus would cause inconsistency in the results obtained.

After that, the lock- in amplifier, which was locked to the chopper frequency, was zeroed when the 90° button was pushed in as this is the instant where the beam was hitting the chopper causing the voltage detected to be only from the background light. The act of zeroing the lock- in amplifier removed background light pollution, improved the signal to noise ratio and diminished the requirement for completely dark conditions. Consequently, when the 90° button was pushed out, only the beam that passes through the chopper was detected. The detector was a silicon photo diode that has passed through a pre- amp stage and was linked to the lock- in amplifier. This decreases the error in the experiment and generates more accurate results.

Subsequently, a Matlab code was written to automate the wavelengths, record and analyse the data measured by the detector to obtain the desired results. This process is shown by the flow diagram on the next page. The wavelength inputted by the user in the code had to be converted into number of steps, as changing the number of steps in the motor by one does not corresponds changing the wavelength on the monochromator by one. This conversion is done by finding the average of the ratio of actual number of wavelength moved to the number of wavelength inputted by the user. Then, dividing the number of wavelength inputted by the user by the ratio determined will convert the number of wavelength inputted into the number of steps to be moved by the motor. This will ensure the number of wavelength moved by the stepper motor on the monochromator and the number of wavelength inputted by the user to be the same.

Then, the experimental set up in conjunction with Matlab m-file was used to obtain the incident, I and transmitted intensities I_0 over the range of wavelength inputted by the user. For GaAs, the range of wavelength covered was from 400nm to 700nm and for GaP, from 750nm to 950nm. Three sets of data, both with and without the sample were obtained from repetition for both direct and indirect band gap sample and the average of these data were calculated.


Start
Reset the DAQ card
Configure DAQ for 8-bit digital output
Configure DAQ for 1 analogue input
Set the sampling rate and the number of samples to be collected per trigger
Calibrated so that motor will move the number of wavelengths specified by user
User input: 'Do you want to go backwards or forwards b/f?'
b/f as specified by user
User input: 'How many wavelengths would you like to move?'
wavelength as specified by user
'b' and wavelength inputted by user
'f' and wavelength inputted by user
Output data to motor: Motor moves backwards according to the wavelength inputted by user
Output data to motor: Motor moves forward according to the wavelength inputted by user
Record input from detector
Has the data been recorded for the whole given wavelength range?
No
Yes
3 repeats for both with and without the samples (GaAs and GaP)
Analysis of data
End

From the average of I and I_0 obtained, the transmission coefficient, T, was determined by applying equation 2. After that, the graphs of transmission coefficient against the range of wavelength used were plotted for both samples. Subsequently, using n= 3.5227 for GaAs and n= 3.1870 for GaP, [18] R were calculated using equation 5. In order to find α from these data, equation 11 derived from equation 3 was used.

$$\alpha = -x^{-1} ln(\frac{[(1-R)^4 + 4T^2R^2]^{1/2} - (1-R)^2}{2TR^2}) \tag{11}$$

where x is the thickness of the sample. The thickness of the GaAs sample is $(0.32 \pm 0.01) \times 10^{-3}$m and the thickness of the GaP sample is $(0.35 \pm 0.01) \times 10^{-3}$m.

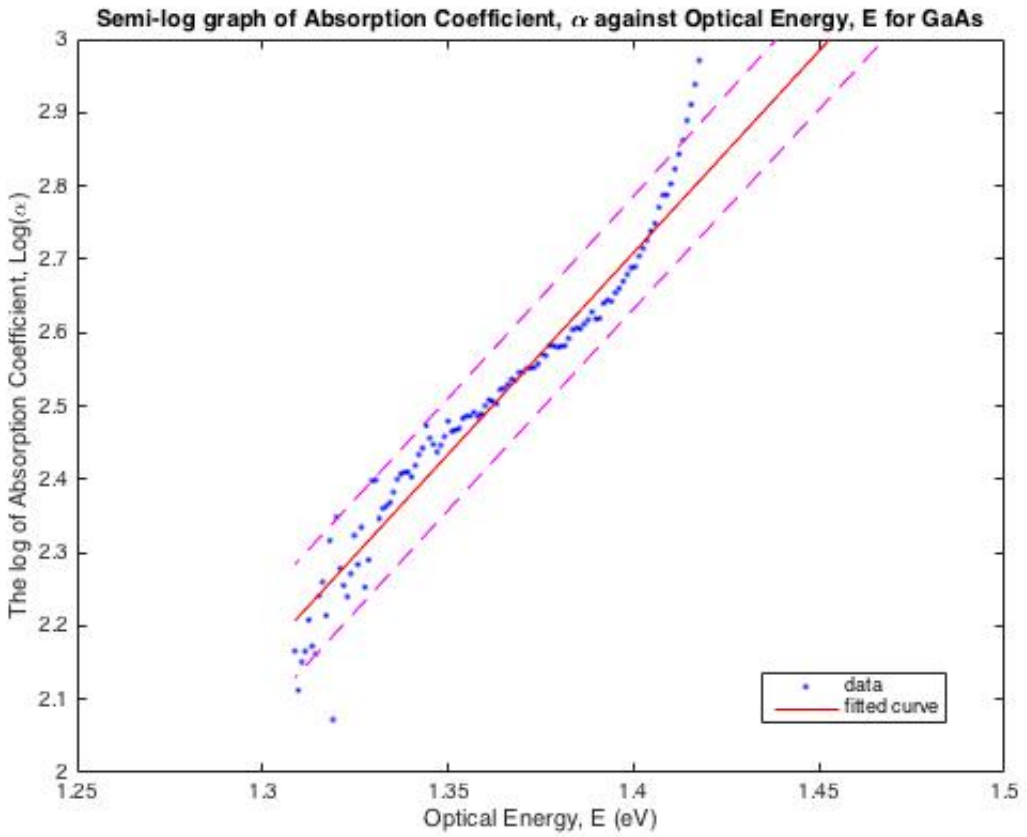
Also, the optical energy, E, had to be calculated in order to plot the data to obtain the desired results. This was done using

$$E = \frac{hc}{\lambda} \tag{12}$$

where h is Planck's constant (6.62×10^{-34}) m^2 kg/s and c is the speed of light in vacuum (3×10^{-8}) m/s.

Consequently, graph of α^2, $\alpha^{1/2}$ and $(\alpha - \alpha_a = \alpha_e)$ against optical energy, E could be plotted and analysed using CFTool. For GaAs, the Urbach slope, E_0 could be found through the gradient of the linear best fit line of the semi-log graph of α against E in the lower energies. The Urbach slope, E_0 will be the inverse of the gradient found from the previous part. The band gap energy of GaAs could be determined by finding the x- intercept of the linear best fit line of the graph of α^2 against optical energy. Finally, for GaP, the graph of $\alpha^{1/2}$ against the optical energy was plotted and the linear best fit line of the lower energies is $\alpha_a^{1/2}$. α_a was then subtracted from α. After that, the square root of the difference $(\alpha - \alpha_a)^{1/2}$ was plotted against the optical energy. The x- intercept of the graph of $\alpha^{1/2}$ against the optical energy is $E_g - E_p$ and for the graph of $(\alpha - \alpha_a)^{1/2}$ against the optical energy is $E_g + E_p$. E_g and E_p could be determined by means of simultaneous equations. [16]

5 Results

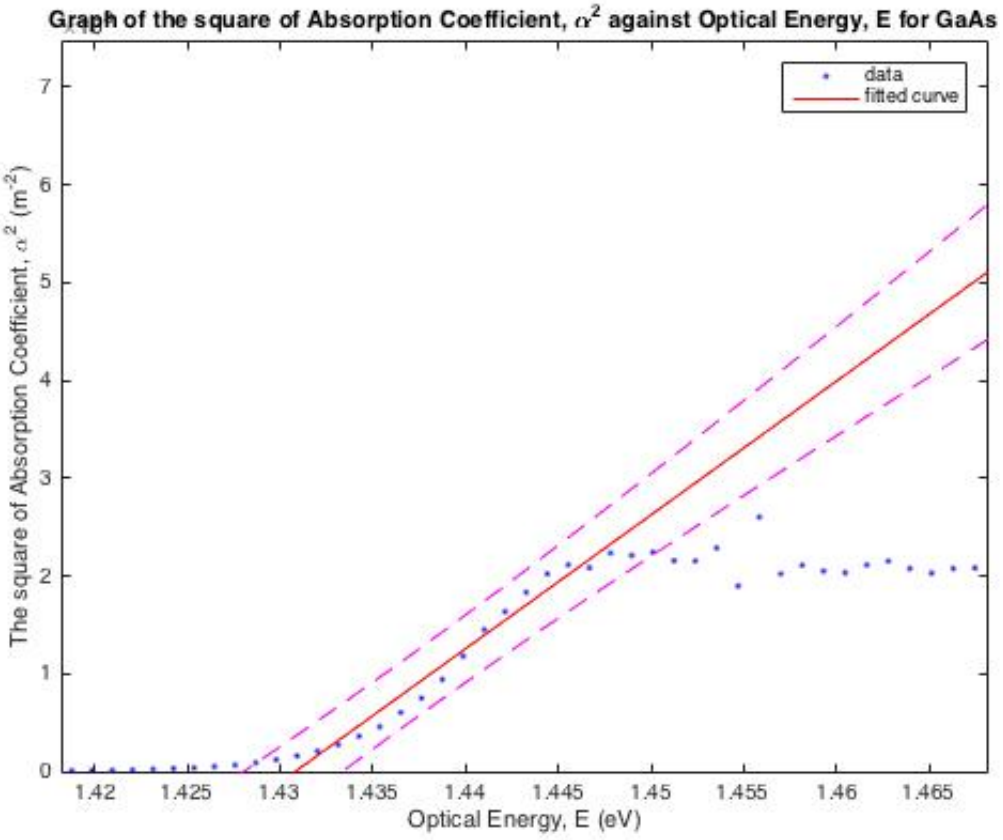


Graph 1: A semi-log graph of absorption coefficient, α being plotted against the optical energy, E, in order to investigate the Urbach slope. The inverse of the gradient of the line of best fit of the band tail is the Urbach slope.

From graph 1, the gradient was found to be (5.502 ± 0.254)eV. The Urbach slope, E_0 could be calculated from the inverse of the gradient. Hence, $\frac{1}{5.502} = (0.182 \pm 0.008)$ eV. The error on the gradient was obtained from CFTool by finding the difference between the value of the gradient and the upper and lower bounds. Then, the error of the Urbach slope could be found by multiplying the value of the Urbach slope with the percentage error from the gradient.

Most of the points lies within the 95% confidence bound of the line of best fit. The

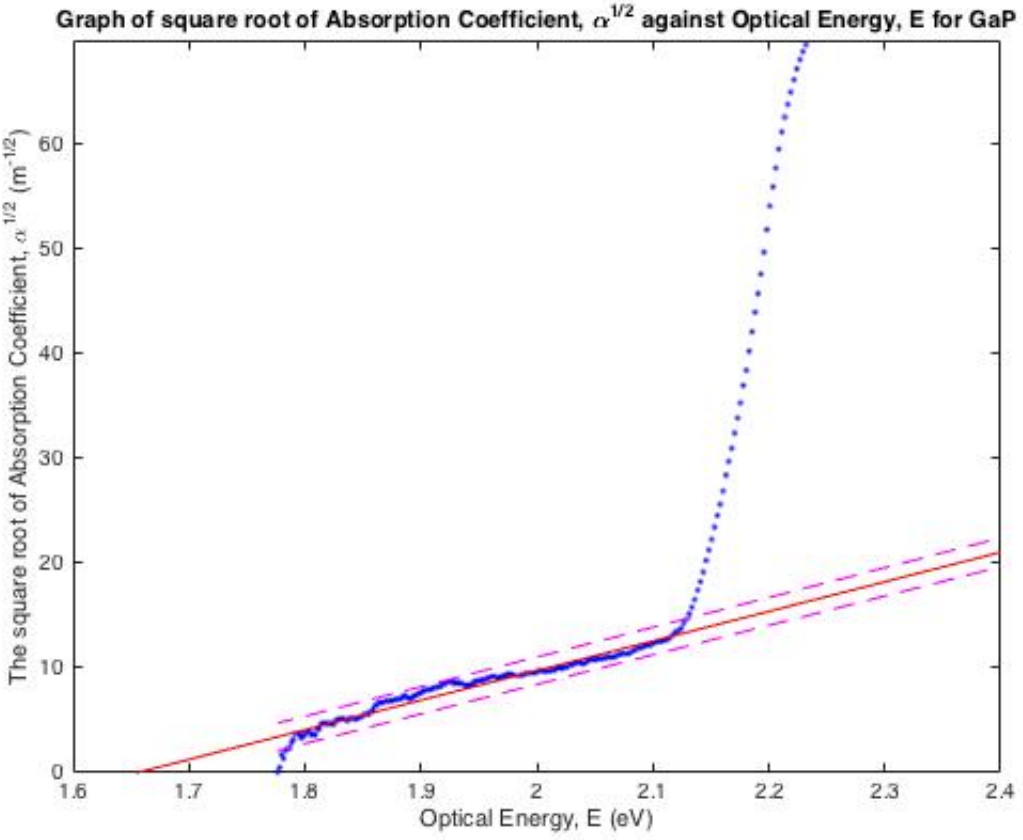
outliers are data that were not included in fit. The points lies on both side of the fit.



Graph 2: A graph of the square of absorption coefficient α^2 being plotted against the optical energy, E, in order to investigate the band gap energy of GaAs. The x-intercept of the line of best fit of the linear part of this graph is the band gap energy.

From the graph 2, the x-intercept was found to be (1.431±0.002) eV. The x-intercept and its error were found by swapping the axes so that it could be determined through CFTool by finding the y-intercept. The error on the y-intercept was obtained from CFTool by finding the difference between the value of the y-intercept and the upper and lower bounds.

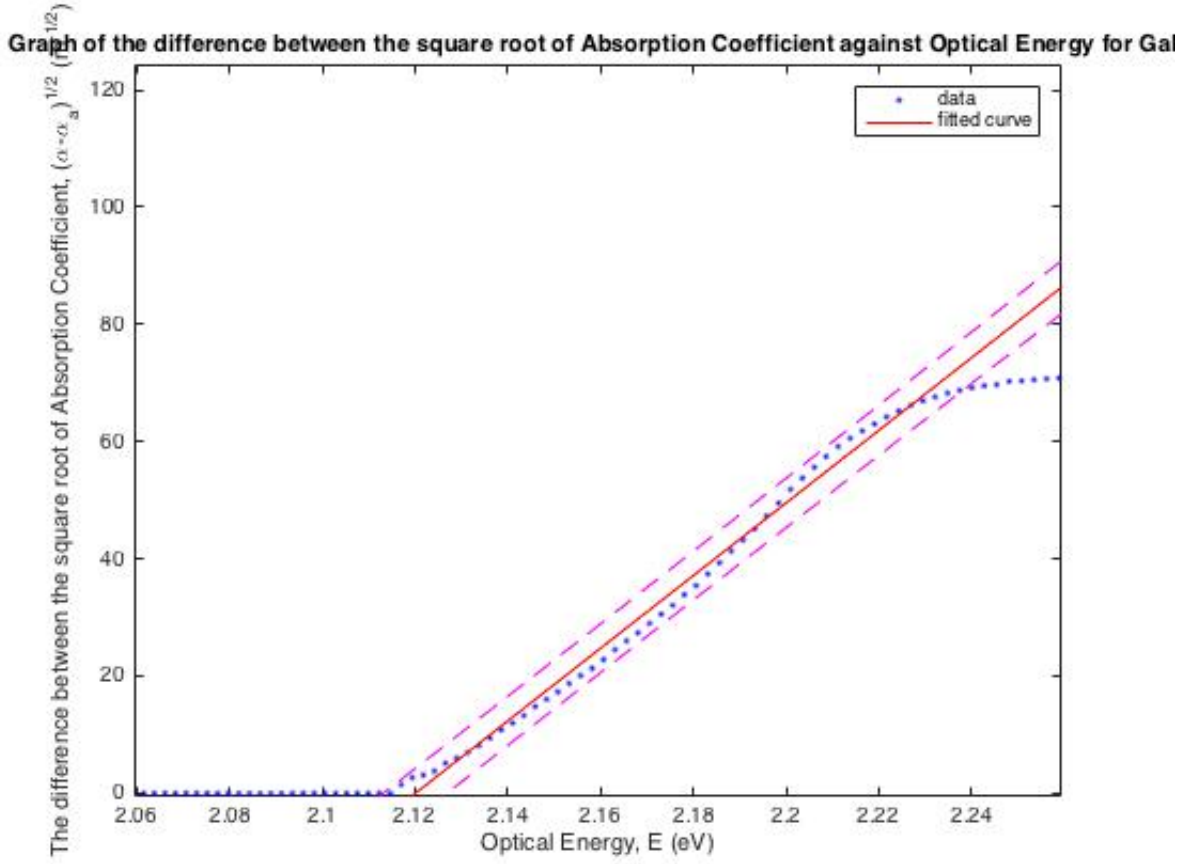
Once again, most of the points lies within the 95% confidence bound of the line of best fit. The outliers are data that were excluded from the fit in CFTool.



Graph 3: A graph of the square root of absorption coefficient, $\alpha^{1/2}$, against optical energy, E, for GaP. The x- intercept of the line of best fit of the linear part of this graph is $E_g - E_p$.

From graph 3, the x- intercept can be seen as roughly (1.66 ± 0.50) eV. The x-intercept and its error were found by swapping the axes so that it could be determined through CFTool by finding the y-intercept. The error on the y-intercept was obtained from CFTool by finding the difference between the value of the y-intercept and the upper and lower bounds. Hence, the actual $E_g - E_p$ was found to be (1.540 ± 0.013) eV. The line of best fit on the graph is α_a.

Most of the point lies within the 95% confidence bound of the line of best fit. The outliers are data that were excluded from the fit in CFTool.



Graph 4: A graph of square root of the difference between the absorption coefficient, $(\alpha - \alpha_a)$ against optical energy, E.The x- intercept of the line of best fit of the linear part of this graph is $E_g + E_p$.

From graph 4, the x- intercept can be seen to be roughly (2.12 ± 0.01) eV. The x-intercept and its error were found by swapping the axes so that it could be determined through CFTool by finding the y-intercept. The error on the y-intercept was obtained from CFTool by finding the difference between the value of the y-intercept and the upper and lower bounds. Hence, the actual $E_g + E_p$ was found to be (2.121 ± 0.002) eV.

Most of the points lies within the 95% confidence bound of the line of best fit. The outliers are data that were excluded from the fit in CFTool. The points lies on both

side of the fit.

Finally, using the discovery of $E_g - E_p$ and $E_g + E_p$, E_g and E_p could be determined through solving simultaneous equation. This gives result of the energy of phonon, E_p to be (0.2905 ± 0.0066) eV and the band gap energy, E_g to be (1.8305 ± 0.0146) eV. The error of the energy of phonon and the band gap energy was found using the error propagation equation for subtracting two different variables.

6 Discussion

The Urbach slope of the exponential band tail in GaAs was calculated to be (0.182 ± 0.008) eV. However, in literature, it is expected to be around the range of (5-7) meV. [16] The result obtained is a factor of (26-36) meV out compared to the literature value. Since the experimental value was obtained through finding the inverse of the gradient of the semi-log graph of absorption coefficient against the optical energy, the gradient should have had a much higher value in order to produce the much lower expected literature value. This implies that a small change in the optical energy should generate a large change in the absorption coefficient. The possible explanation for this inaccuracy is working with the wrong set of apparatus, as the set of apparatus intended for GaP was used to carry out this experiment. The set of apparatus for GaP was slightly different as explained in the experimental method section, less suitable for GaAs because the range of wavelength used for GaAs is higher.

On the other hand, the band gap energy for GaAs was found to be (1.431 ± 0.002) eV experimentally. In spite of using the wrong set of apparatus, astonishingly, the experimental result obtained is accurate up to 2 decimal places in comparison to the literature value of 1.43 eV at room temperature. [19]

Then, the band gap energy for GaP was found to be (1.8305 ± 0.0146) eV experimentally. It is approximately 0.4 eV lower than the expected literature value of 2.25 eV at room temperature. [19] The plausible explanation for this inaccuracy is extrapolating the incorrect section of the data on the graph as the lower part of the graph that was extrapolated is suspected to be a band tail. As seen on graph 3 and graph 4 in the results section, although subtle, the plot between 2.1 eV and 2.3 eV on graph 3, and 2.12 eV and 2.22 eV on graph 4 could have been extrapolated as two different line of best fit. This would produce a value of band gap energy for GaP that is closer to the literature value. However, in an actual experiment, there would be no reference value to be compared to, hence, the result was left as it is.

There are several other factors that contributes to the error in the experiment.

The monochromator used in the experiment does not have a high level of precision as it operates on discrete scale that are only accurate up to a single digit and also, it is controlled by a stepper motor that changes it in steps. The scale on the monochromator occasionally ends up in between two values. This could be improved by replacing it with a better monochromator with a higher level of precision. Other than that, the alignment of the apparatus will not produce the maximum intensity achievable experimentally. Also, there will be consequential error in the calculated value of R as the refractive index of the samples are obtained from literature and usually, refractive index varies over a range of values. In this case, the values used in calculations for this experiment are not necessarily the same as the actual refractive index of the samples used in the experiment. Also, impurities on the sample could contribute towards the error obtained in the results.

7 Conclusion

The lock- in detection method carried out using the apparatus and samples provided in conjunction with Matlab was employed to investigate different quantities of the direct and indirect band gap. The Urbach slope was found to be (0.182 ± 0.008) eV, the band gap energy for a direct band gap semiconductor to be (1.431 ± 0.002) eV, the energy of phonon to be (0.2905 ± 0.0066) eV and the band gap energy for an indirect band gap semiconductor to be (1.8305 ± 0.0146) eV. The results obtained are fairly reliable as there are minimal error. However, some of the results obtained were not consistent with literature value as the wrong set of apparatus were used and the wrong section of the graph were extrapolated. Once again, semiconductors plays an important part in our everyday life, hence, this is an area that is worth looking into more deeply.

8 Appendices

Table of Contents

..... 1
Setting up output 1
Setting up input 1
Moving motor 1
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Analysis of the indirect band gap sample 5

```
% Chong Hui Yong@ Ruby
% Optical absorption of semiconductors
% 26th February 2016
```

Setting up output

```
daq.reset
clear, close all;
clc;
s = daq.createSession('ni');
% Creates session object
s.addDigitalChannel('Dev1','Port0/Line0:7','OutputOnly');
% Adds 8 digital output channels (numbered 0:7) on the DAQ card
```

```
Undefined variable "daq" or class "daq.reset".

Error in FINALCODE (line 6)
daq.reset
```

Setting up input

```
s1 = daq.createSession('ni');
% Creates session object
s1.addAnalogInputChannel('Dev1',0,'Voltage');
% Adds 1 analog input channel (numbered 0) on the DAQ card
s1.Rate = 1000; s1.NumberOfScans = 1000;
% Rate is the number of samples collected per second
% Number of scans is the total number of samples to be collected per
% trigger
intensity=[];
% Emptry matrix to be filled in as the code runs from the loop
```

Moving motor

```
nout = [51 102 204 153];
% This is the decimal sequence for forward motion

borf=input('Do you want to go backwards or forwards b/f ? ','s');
% Obtaining information from the user in terms of string and stores
 the
```

```
% result in the variable 'borf'
number_wavelength=input('How many wavelengths would you like to move?
 ');
% Obtaining the number of wavelength to be moved and stores the
% result in the variable 'number_wavelength'

% If the user inputted 'b', the wavelength will move backwards
% whereas 'f', the wavelength will move forward
% This loops changes the wavelengths in steps while obtaining the data
if borf == 'b'
    count=4;
    % As it is going backward, start from the last (4th) element of
 the
    % decimal sequence of the stepper motor and work backwards
    for n =1 : round(number_wavelength/0.6584);
        % This converts the number of wavelength into data index in
 order
        % for the motor to change the number of wavelength
        % on the monochromator
        outputSingleScan(s,dec2binvec(nout(count),8));
        % This will output the m bit binary representation converted
        % from integer #number# to command the stepper motor to
        % alter the wavelength of the monochromator
        [data,timestamps] = startForeground(s1);
        intensity(n)= mean(data);
        % This inputs data into the empty matrix 'intensity'
        plot(n,intensity(n),'*');
        % This will show the graph of intensity against data index
 being
        % plotted every iteration of the loop until the loop is
        % terminated
        hold on;
        count=count-1;
        % This is so that the decimal sequence work backwards every
        % iteration
        if count==0
            count=4;
        end
        % When the count decreases to 0, reset it to 4 again so that
 the
        % stepper motor keeps moving backward
     pause(0.05);
    end

end

if borf == 'f'
    count=1;
    % As it is going forward, start from the first element of the
    % decimal sequence of the stepper motor and work forward
    for n=1 : round(number_wavelength/0.6584);
        % This converts the number of wavelength into data index in
 order
        % for the motor to change the number of wavelength
```

```
        % on the monochromator
        outputSingleScan(s,dec2binvec(nout(count),8));
        % This will output the m bit binary representation converted
        % from integer #number# to command the stepper motor to
        % alter the wavelength of the monochromator
        [data,timestamps] = startForeground(s1);
        intensity(n)= mean(data);
        % This inputs data into the empty matrix 'intensity'
        plot(n,intensity(n),'*');
        % This will show the graph of intensity against data index
 being
        % plotted every iteration of the loop until the loop is
        % terminated
        hold on;
        count=count+1;
        % This is so that the decimal sequence work forward every
        % iteration
        if count==5
            count=1;
        end
        % When the count increases to 5, reset it to 1 again so that
 the
        % stepper motor keeps moving forward
        pause(0.05);
    end
end
```

Analysis of direct band gap sample

```
clear all; close all; clc;
% Load saved workspace data
I_dw1=dlmread('datadirectw1.txt').';
I_dw2=dlmread('datadirectw2.txt').';
I_dwo1=dlmread('datadirectwo1.txt').';
I_dwo2=dlmread('datadirectwo2.txt').';

% Calculates the mean of the intensity with and without the sample
% recorded by the detector
Intensity_1= (I_dw1+I_dw2)./2;
Intensity_0= (I_dwo1+I_dwo2)./2;

% The wavelength over which the measurements were taken
wavelength_direct= (750:0.67567568567:950).*10.^-9;


T_1= Intensity_1./Intensity_0;
% Equation to calculate the tranmission coefficient
T_1min= min(T_1)
% Finding the minimum of the transmission coefficient
T_2= T_1+(-T_1min);
% Adding the difference between 0 and the minimum of transmission
% coefficient to the rest of the points so there will be no negative
% y value
```

```
plot((wavelength_direct), T_2);
% This plots the transmission coefficient against the wavelength
xlabel('Wavelength (m)')
ylabel('Transmission coefficient')
title('Graph of transmission coefficient against wavelength for GaAs')
% These labels the plot

% Constants
n_GaAs= 3.5227; %http://refractiveindex.info/?
shelf=main&book=GaAs&page=Skauli
% The refractive index of GaAs

R_GaAs= [(n_GaAs-1)./(n_GaAs+1)].^2;
% Equation to calculate R

x_GaAs= 0.32.*10.^-3 ;
error_GaAs= 0.01.*10.^-3 ;
% The thickness of the GaAs sample and it's error

a=(1-R_GaAs).^4;
b=4.*(T_2.^2).*((R_GaAs).^2);
c=(a+b).^0.5;
d=(1-R_GaAs).^2;
numerator=c-d;
denominator=2.*T_2.*(R_GaAs.^2);
logterm=numerator./denominator;
Alpha_GaAs=(-x_GaAs.^-1).*log(logterm);
% Equation to calculate alpha of GaAs

h= 6.62607004.*10.^-34;
% Planck's constant
c= 3.*10.^8;
% Speed of light
E_direct= ((h.*c)./(wavelength_direct))./(1.6.*10.^-19);
% Equation to calculate the optical energy
LogAlpha_GaAs= log10(Alpha_GaAs);
% Calculating the log of Alpha_GaAs
Alpha_squared= (Alpha_GaAs).^2;
% Calculating the square of Alpha_GaAs

%cftool
% Using curve fit tool to plot graph and analyse the data
% Semi- log graph of absorption coefficient against optical energy
% and graph of square of absorption coefficient against optical energy
% was plotted.


pbs = predint(fittedmodel,E_direct,0.95);
plot(fittedmodel,E_direct,LogAlpha_GaAs);
hold on;
ylabel('The log of Absorption Coefficient, Log(\alpha)')
xlabel('Optical Energy, E (eV)')
title('Semi-log graph of Absorption Coefficient, \alpha against
 Optical Energy, E for GaAs')
```

```
plot(E_direct,pbs,'m--');
xlim([1.25 1.5])
ylim([2 3])
% Semi log graph of absorption coefficient against optical energy with
 its
% line of best fit and 95% confidence bound are plotted and the graph
% labelled.
% The same is repeated for the graph of square of absorption
 coefficient
% against optical energy.
```

Analysis of the indirect band gap sample

```
clear all; close all; clc;
% Load saved workspace data
I_idw1=dlmread('dataindirectw1.txt').';
I_idw2=dlmread('dataindirectw2.txt').';
I_idw3=dlmread('dataindirectw3.txt').';
I_idwo1=dlmread('dataindirectwo1.txt').';
I_idwo2=dlmread('dataindirectwo2.txt').';
I_idwo3=dlmread('dataindirectwo3.txt').';

% Calculates the mean of the intensity with and without the sample
% recorded by the detector
Intensity_1= (I_idw1+ I_idw2+ I_idw3)./3
Intensity_0= (I_idwo1+ I_idwo2+ I_idwo3)./3;

% The wavelength over which the measurements were taken
wavelength_indirect= (400:0.65789473694:700).*10.^-9;

T_1= Intensity_1./Intensity_0;
% Equation to calculate the tranmission coefficient
T_1min= min(T_1)
% Finding the minimum of the transmission coefficient
T_2= T_1+(-T_1min);
% Adding the difference between 0 and the minimum of transmission
% coefficient to the rest of the points so there will be no negative
% y value
plot((wavelength_indirect), T_2);
% This plots the transmission coefficient against the wavelength
xlabel('Wavelength (m)')
ylabel('Transmission coefficient')
title('Graph of transmission coefficient against wavelength for GaP')
% These labels the plot

% Constants
n_GaP= 3.1870; %http://refractiveindex.info/?
shelf=main&book=GaP&page=Jellison
% The refractive index of GaP

R_GaP= [(n_GaP-1)./(n_GaP+1)].^2;
% Equation to calculate R
```

```
x_GaP= 0.35.*10.^-3 ;
error_GaP= 0.01.*10.^-3;
% The thickness of the GaAs sample and it's error

a=(1-R_GaP).^4;
b=4.*(T_2.^2).*((R_GaP).^2);
c=(a+b).^0.5;
d=(1-R_GaP).^2;
numerator=c-d;
denominator=2.*T_2.*(R_GaP.^2);
logterm=numerator./denominator;
Alpha_GaP=(-x_GaP.^-1).*log(logterm);
% Equation to calculate alpha of GaP

h= 6.62607004.*10.^-34;
% Planck's constant
c= 3.*10.^8;
% Speed of light
E_direct= ((h.*c)./(wavelength_indirect))./(1.6.*10.^-19);
% Equation to calculate the optical energy
minGaP= min(Alpha_GaP);
% Finding the minimum value of Alpha_GaP
AlphaGaP= Alpha_GaP+(-minGaP);
% This is so that there will be no negative y- value

Alpha_root=(AlphaGaP).^0.5;
% This is to calculate the square root of AlphaGaP

%cftool
% Curve fit tool used to obtain information about the plot

Eindirect= linspace(1.6,3.2,456)
% This generates 456 points between 1.6 and 3.2
alpha_a= 28.29.*Eindirect+(-46.87)
% Calculates the value of alpha corresponding to the value of
 Eindirect
% generated in the previous part


Alpha_root2= 28.29.*E_indirect+(-46.87);
% This generates the value of square root of absorption coefficient
% obtainend from the fit plotted in cftool in the previous part
Alpharoot2= Alpha_root2;
% This creates a variable that has the value of Alpha_root2 so that if
 it
% is modified the value of Alpha_root2 will not be affected
Alpharoot2square= (Alpharoot2).^2;
% This removes the square root on the alpha
Alpharoot1= Alpha_root;
% This creates a variable that has the value of Alpha_root so that if
 it
% is modified the value of Alpha_root will not be affected
Alpharoot1square= (Alpharoot1).^2;
% This removes the square root on the alpha
```

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```
actualdifference= Alpharoot1square-Alpharoot2square.';
% This calculates the difference between the alpha without square root
 on
% the alpha
finalroot= sqrt(actualdifference);
% This square root the difference between the alpha found in the
 previous
% part
ActualAlpharootfinal= finalroot;
% Renaming the previous part with ActualAlpharootfinal

%cftool
% Curve fit tool is used to find the line of best fit for the graph of
% square root of the absorption coefficient against the optical energy
 and
% for the graph of square root of the difference between the alpha
 against
% optical energy


pbs = predint(fittedmodel, E_indirect,0.95);
plot(fittedmodel, E_indirect, ActualAlpharootfinal);
hold on;
set(0,'DefaultTextInterpreter','tex')
ylabel('The difference between the square root of Absorption
 Coefficient, (\alpha-\alpha_a)^{1/2} (m^{-1/2})')
xlabel('Optical Energy, E (eV)')
title('Graph of the difference between the square root of Absorption
 Coefficient against Optical Energy for GaP')
plot(E_indirect,pbs,'m--');
% Graph of square root of the absorption coefficient against the
 optical
% energy and the graph of square root of the difference between the
% alpha against optical energy together with their line of best fit
 and 95%
% confidence bound are plotted and the graph labelled.
```

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