

# Thor Labs Possible Detectors

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Optical fibers - increase gain

Look at all the options

# Initial Meeting

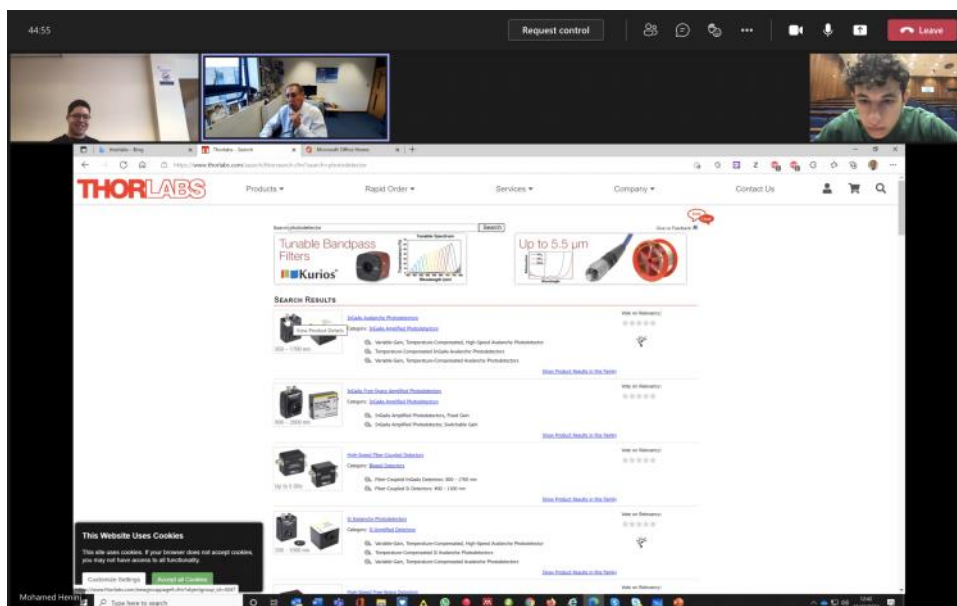
Friday, 15 October 2021 19:44

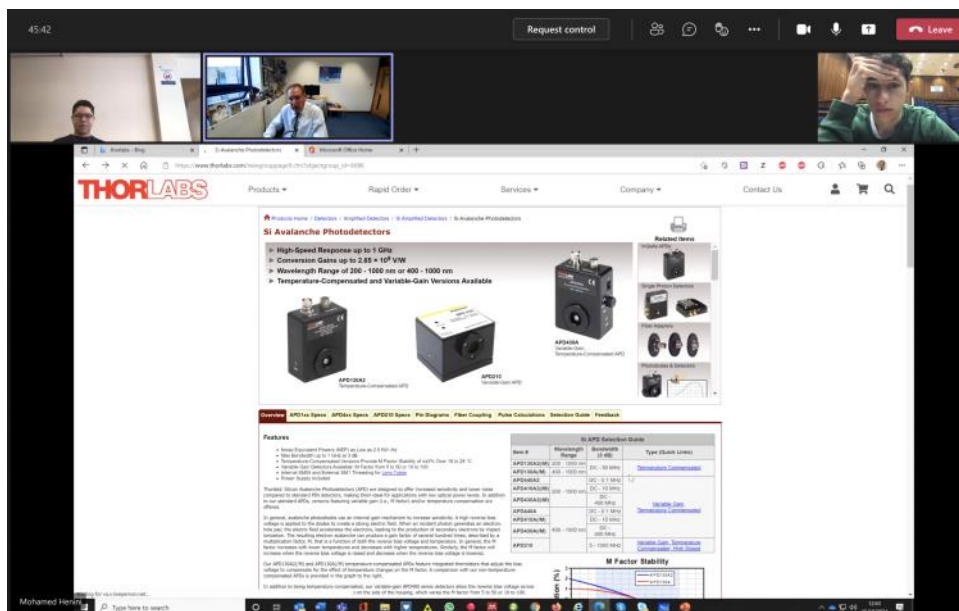
This is the first meeting regarding the project. This meetings was mainly an introductory meeting where Mohamed Henini went over the basics of semiconductors and briefly described what the project would entail, which was:

1. setting up an automated optical system
2. writing a bit of software to drive/monitor different components of the system
3. ultimately calculating the bandgap of said semiconductor

As I had already completed a similar optical absorption experiment in second year, meeting was more of a reminder to refresh my memory on the basics again without going into too much detail. For Jake on the other hand it acted more as an introductory lecture as I believe he hasn't done a similar project before.

It was established in the meeting that we would have to buy some equipment for this experiment in the form of a avalanche photodetector. The photos below are what were suggested by Mohamed. It is very similar to the year two experiment apart from no lockin detector and this means no chopper either.





After the meeting Mohamed he kindly sent over the lecture slides which are attached at the bottom. Also attached was a paper detailing a method of calculating a method of calculating the bandgap via near band edge optical absorption. After reading through the paper I established this experimental is similar but not identical to the one we shall use in this experiment.

## Key Take Aways:

- Similar to Y2 project
  - o No lockin in this experiment
  - o Avalanche photo detector instead
- Need to purchase Avalanche photo detector if matt young doesn't have any similar equipment
- Read through the paper and the papers experiment is marginally different
  - o No optical absorption as no transmission data
  - o Simpler than said experiment

## Tasks To-do:

- Think about possible photodetectors to but and the right wavelength ranges

# Another Meeting

Friday, 22 October 2021 19:17

- Very short meeting with Mohamed, just to clarify a few things regarding the equipment and how to acquire it / who do we speak to.
- Was confirmed that it all goes through Matt Young for the equipment
- Showed possible photo detector purchases which he said might be a good fit
  - o Still need to check with matt first to see if he has any similar equipment
- Jake emailed Matt regarding when we could attend the labs to see the equipment and familiarise ourselves with it
  - o Monday is the agreed time

## Key Take Aways:

- Go through matt for all equipment related questions and issues / purchases

## Tasks To-do:

- Chase matt about the equipment - when can we see it
- Ask matt about the photodetector
- Go into the Lab on monday

# Visited Lab

Monday, 25 October 2021 20:09

- Went into the lab to see the equipment in the 3rd Year lab
- Recognisable from the previous experiment
- Asked about the photodetector and he said he would have a look
- Python script for the automation - ask matt for it
- MATLAB script for analysis

## Key Take Aways:

- Matt will look for applicable detector

## Tasks To-do:

- Enquire about the python script
- Have a look at code from previous experiment

# Progress Check

Friday, 10 December 2021 19:18

## Accomplished so far:

- Established & refreshed the basics of semiconductors
- Seen and viewed the equipment
- Enquired about the photodetector
- Had several meetings with Mohamed regarding the project and steps to make

Nothing much but background research and enquiring about the photo detector needs to be done thus far. After my other modules have been finished such as gravity and QCD I will start to undertake the literature review

## Task To-Do

- Start to think about Lit review
- Review Python / MATLAB code
- Further enquire about photodetector

# Meeting

Wednesday, 22 December 2021 21:01

Mohamed wanted a meeting before Christmas so both Jake and I attended. Another short meeting discussing progress from last time:

- Not much progress to report as I was focussing on my other modules Gravity and QCD
- Still pending email back from matt re python script
- Read a bit of the lit report, which I will now start to embark on
- Will have a think about the MATLAB code for the analysis
  - o I have some example data from the previous experiment which I will now use for the basis to check my code is working.
- Diary will be empty for a few days - going on holiday and taking a bit of a break from work entirely

# Initial Commit

Sunday, 2 January 2022 10:03

- Started a GitHub to monitor and track all the files of this report
  - o Took a bit of time to set up but will be worth it
  - o It will track all the code and tex changes
  - o Also a good place to collaborate with Jake and share documents

## Tasks To-Do:

- Think about the automated process in python and MATLAB
  - o Starting with MATLAB



# Tikz

Sunday, 2 January 2022 12:06

For the formal report I have found that for optical absorption, there are a lack of consistent diagrams. Many of the diagrams are good but lack consistency with the style and labelling. For the lit review and report at the end of the year there needs to be a sense of consistency between all the figures. So I have decided to learn how to use Tikz for LaTeX. This will allow be to make my own custom figures and therefore be fully consistent through the experimental report.

For the first day learning Tikz I embarked on very simple projects, the following code was the result of a days work with the results yielded in the pdf at the bottom. Threse are just the basics of Tikz as I try and get to grasps with it.



TikzFigures



TikzFigures

# Changing n in code

Monday, 3 January 2022 11:51

- In [1], the paper provided, it has been established that a approximate value of n was used throughout the whole experiment.
- However the value of n does change throughout the range so I will create code which will take the nearest wavelength and return the appropriate value of n for that given wavelength:

% loads all the data for this experiment

```
RefractiveIndexInfo = csvimport('/Users/harold/Documents/Academia/Nottingham Uni/Year  
4/Research Project/Report/Coding/RefractiveIndexINFO.csv');  
RefractiveIndexInfo(1,:) = [];  
%RefractiveIndexInfo_GaAs = cellfun(@str2double, RefractiveIndexInfo_GaAs);  
RefractiveIndexInfo_GaAs = zeros(46,3);
```

```
for c=1:3  
    for r=1:46  
        RefractiveIndexInfo_GaAs(r,c) = RefractiveIndexInfo{r,c};  
    end  
end
```

```
L = RefractiveIndexInfo_GaAs(:,1).*1000;  
N = RefractiveIndexInfo_GaAs(:,2);  
K = RefractiveIndexInfo_GaAs(:,3);
```

```
plot(L,N)  
hold on  
plot(L,K)  
hold off
```

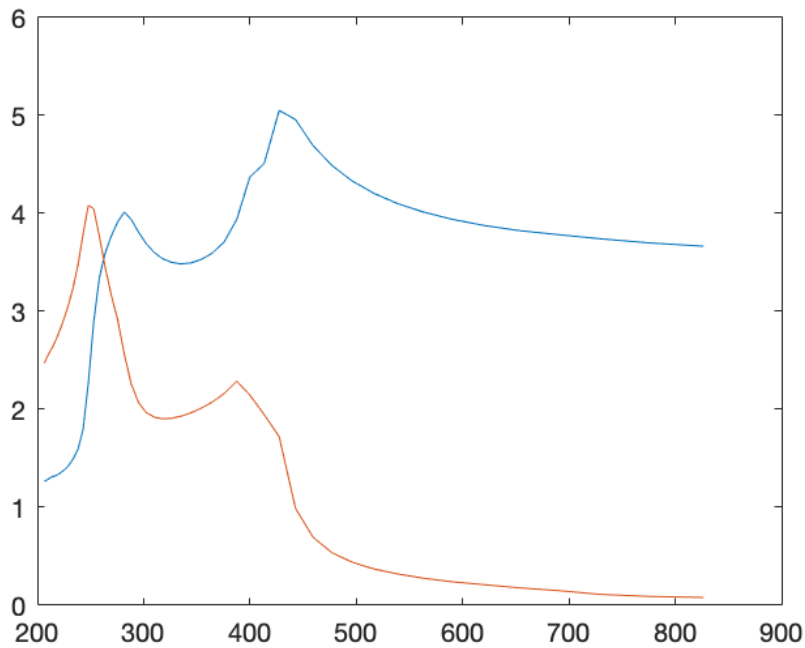
```
function RefractionTrueValue = nearestRefraction(LambdaStore, Lambda, RefractionIndex)
```

```
lambda_d = Lambda-LambdaStore;  
lowest=max(find(lambda_d>0));  
highest=lowest+1;
```

```
n_d = RefractionIndex(highest)- RefractionIndex(lowest);
```

```
Lambda_Percentage = lambda_d(lowest)./(LambdaStore(highest)-LambdaStore(lowest));
```

```
if n_d > 0  
    RefractionTrueValue = RefractionIndex(lowest) - (n_d).* Lambda_Percentage;  
elseif n_d < 0  
    RefractionTrueValue = RefractionIndex(lowest) + (n_d).* Lambda_Percentage;  
else  
    disp('Error Alert')  
end  
end
```



With this code when a wavelength is inputted. It will calculate the nearest two wavelengths from the data provide. Then it will interpolate between those two points to find the percentage between those two values to provide a highly accurate value for the refractive index, both real (blue) and complex (red).

1. Essick, John & Mather, Richard. (1993). Characterization of a bulk semiconductor's band gap via a near-absorption edge optical transmission experiment. American Journal of Physics - AMER J PHYS. 61. 646-649. 10.1119/1.17173.

# Visit to Labs

Tuesday, 25 January 2022 13:19

- Went into labs to establish a few things which we were unsure about regarding the experiment
- Acquired the python script from matt regarding the automated data collection, however this needs to be modified as this script uses a lock in amplifier which we will not be using



- Bentham\_E  
xample\_...
- Matt told us a few things to be wary off regarding the equipment and its calibration

## What we need todo:

- **Don't switch it off**, keeping it running for the whole day
- **Keep it running 15 minutes** before starting the experiment
  - o Gives it time to warm up and shine at a constant colour frequency
  - o Edit the code such that the multi-meter and not the lock in is involved
- Need to **correct for the offset on the monochromator**
  - o Less hassle than calibrating the monochromator itself
- The **light from the bulb has a colour profile**, therefore differing wavelengths will produce differing intensities and therefore voltage.
  - o This needs to be normalised such that the voltage for all the wavelengths is the same at the max intensity
  - o Could run a test across all the wavelengths to get the colour profile of our bulb
- The **photodiode also has its own sensitivity profile** and that will have to be taken into account
  - o Visible in the data booklet

# Meeting Tony Kent

Tuesday, 4 January 2022 16:31

- Met with Tony Kent today to discuss Academic Plagiarism that could arise from similar deviations from the Y2 experiment.
- Was established it would be fine for the mathematics but the main bulk could be plagiarised.

# Curve Fitting

Wednesday, 5 January 2022 13:54

For the automated aspect I thought it would be prudent to automate the fitting of the curve in MATLAB. Firstly I coded the curve fitting aspect

```
function [fitresult, gof] = createFit(xdata_line, ydata_line)
%CREATEFIT(LAMBDASTRAIGHTLINE,STRAIGHTLINE)
% Create a fit.
%
% Data for 'Straight Line Best Fit' fit:
%   X Input : LambdaStraightLine
%   Y Output: StraightLine
% Output:
%   fitresult : a fit object representing the fit.
%   gof : structure with goodness-of fit info.
%
% See also FIT, CFIT, SFIT.
% Auto-generated by MATLAB on 04-Jan-2022 23:31:20

%% Fit: 'Straight Line Best Fit'.
[xData, yData] = prepareCurveData( xdata_line, ydata_line );
% Set up fittype and options.
ft = fittype( 'poly1' );
% Fit model to data.
[fitresult, gof] = fit( xData, yData, ft );
% Create a figure for the plots.
figure( 'Name', 'Straight Line Best Fit' );
% Plot fit with data.
subplot( 2, 1, 1 );
h = plot( fitresult, xData, yData, 'predobs', 0.9 );
legend( h, 'StraightLine vs. LambdaStraightLine', 'Straight Line Best Fit', 'Lower bounds (Straight Line Best Fit)', 'Upper bounds (Straight Line Best Fit)', 'Location', 'NorthWest', 'Interpreter', 'none' );
% Label axes
xlabel( 'LambdaStraightLine', 'Interpreter', 'none' );
ylabel( 'StraightLine', 'Interpreter', 'none' );
grid on
% Plot residuals.
subplot( 2, 1, 2 );
h = plot( fitresult, xData, yData, 'residuals' );
legend( h, 'Straight Line Best Fit - residuals', 'Zero Line', 'Location', 'NorthEast', 'Interpreter', 'none' );
% Label axes
xlabel( 'LambdaStraightLine', 'Interpreter', 'none' );
ylabel( 'StraightLine', 'Interpreter', 'none' );
grid on
```

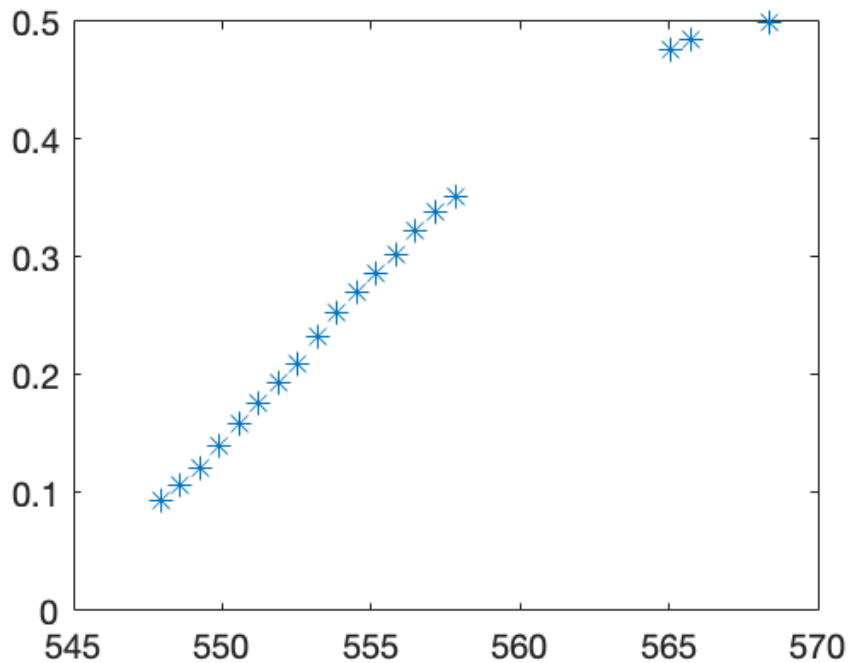
This plots the straight line for a given bit of data and also the residuals to test how good the fit is. However for an automated process the code need to know what points to apply the straight line to. So the following bit of code will identify a straight line section of a curve. Then it will proceed to splice the data in the curve so that only the straight-line fit remains. In essence this code works by finding 3 points where the 2 gradients between three said points is similar, if this is the case it will add it into an array called straight line.

```
function StraightLine = DetectStraightLine(data)
data = smoothdata(data);
StraightLine = [];
for i = 1:size(data,2)
    section = data(i:i+1)
    p12 = section(i)
    p23 = section(i+1)
    per = p23*0.05
```

```

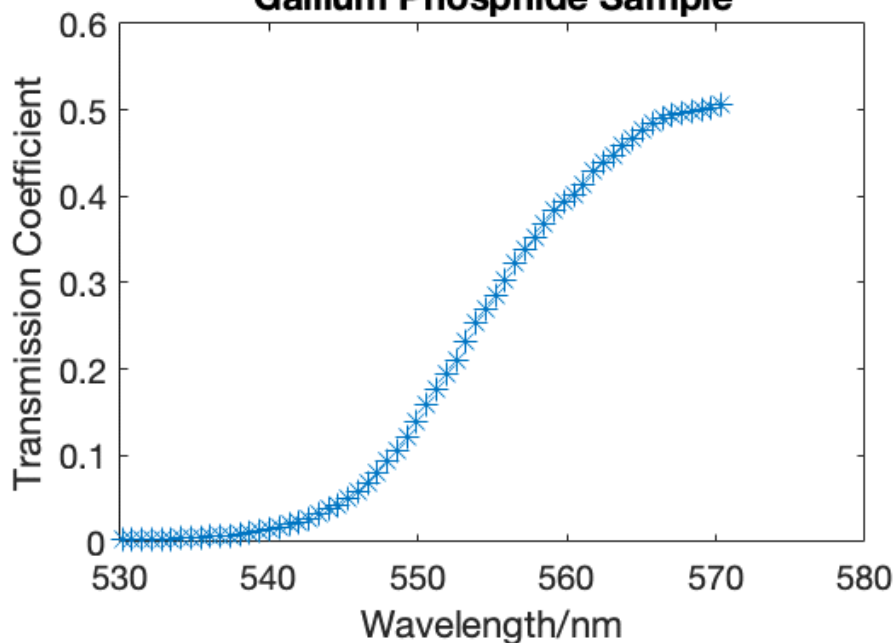
if (p23-per <= p12) && (p12 <= p23+per)
    StraightLine(i) = section(i)
end
end
end

```



This is the output from said function from:

### Transmission Coefficient vs Optical Wavelength taken Gallium Phosphide Sample



Which is selecting the straight line points in the data set. The straight line section being the region of interest. However as seen it has outliers which are not part of the straight line but still with similar gradient. Therefore, the longest straight line aspect needs to be taken into account, by the following code:

```

function [LongestConsecutive, longestLengthIndex] = LongestConsecutive2(X)

```

```

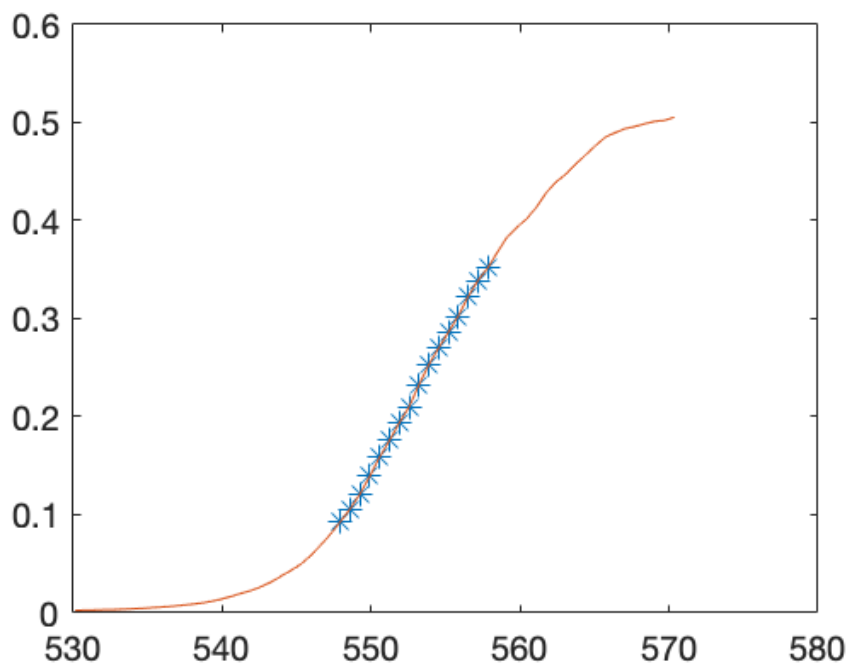
longestLength = 0
longestLengthIndex = []

currLength = 1
size(X)
for i = 1:size(X,2)-1
    if X(i+1) == X(i) + 1
        currLength = currLength + 1;
        longestLength = max(longestLength, currLength);
    else
        currLength = 1;
    end
    LongestConsecutive = max(longestLength, currLength);
    if currLength == longestLength
        longestLengthIndex = i+1;
    end
end

end
end

```

Which yields the following



Which is exactly what we want.



# More Coding

Thursday, 6 January 2022 18:36

- Today didn't yield much progress as there were some problems with the code with the dummy data.
- Spent time sorting them into functions and simplifying the code
- See GITHUB for changes made
- Separated indirect and direct bandgaps into separate analysis functions as they require a different analysis

# Problem Straight Line

Friday, 7 January 2022 19:55

- Realised the straight line code may be flawed if the data isn't ideal
- If the gradient fluctuates randomly it can the straight line not to be picked up
- Trying to find a solution to this
  - o Possibly fitting a spline curve?
- Not much progress as trying to overcome this problem

# Correspondence with Matt

Tuesday, 11 January 2022 15:59

It was established that Matt has something that could be used for the photodetector. SO at the moment there is no need to but anything.

# Safety Files

Tuesday, 18 January 2022 14:05

Spent time creating the safety files such as the COSHH, safety, checklist and risk assessment form.



coshh excel



MSCIPRojec  
t safety\_C...



MSCIPRojec  
t safety\_L...



Risk\_Assess  
ment\_Op...

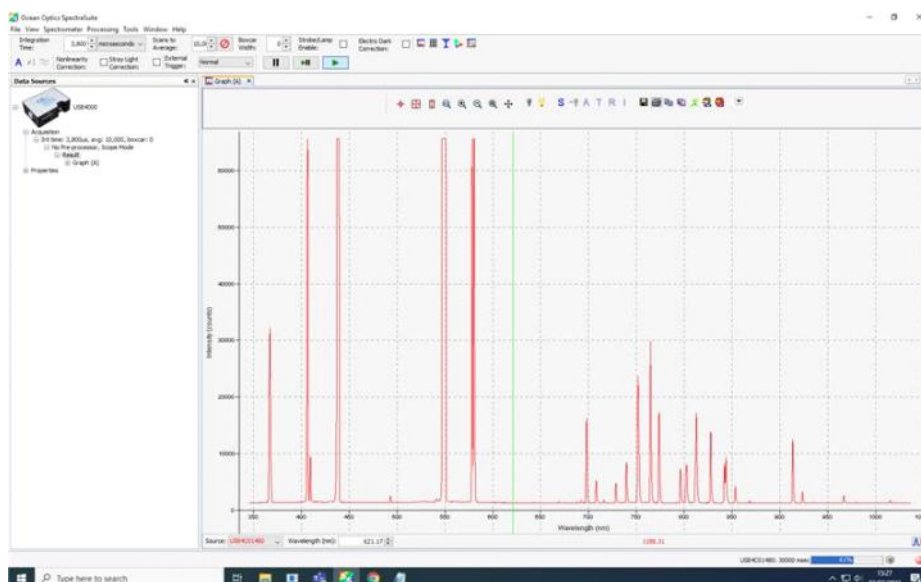
# Day 1 in lab (edit needed)

Tuesday, 1 February 2022 15:38

- With a step motor, head only in one direction. Either from short wavelength to long or vice versa.
- Getting two peaks on our Ocean optics spectrometer from monochromator
- When the spectrometer was plugged into the calibrator, we realised there were no longer two peaks, implying that the peaks were coming from the monochromator.
- Need to calibrate ocean spectrometer.
  - o Using 4 milliseconds integration time we got a wavelength spectrum from our Hg/Ar calibration source.
    - We use the 4 milliseconds integration time as it gives us too many photons when the photon number is higher.
  - o We averaged the spectrum over 150 scans to stabilise the fluctuations in the spectrum.
  - o This was then paused to keep the spectrum steady.
  - o The wavelength range 350nm to 1000nm

Expected wavelength (nm)	Predicted wavelength (nm)
365.015	366.90
404.656	406.46
407.783	409.60
435.833	437.58 - cannot be used as the peak is maxed out.
546.074	548.48 - cannot be used as the peak is maxed out.
576.960	578.71
579.066	580.72
696.543	698.17
706.722	708.36
710.748	N/A
727.294	728.82
738.393	739.84
750.387	751.95
763.511	765.11
772.376	773.91
794.818	796.41
800.616	802.69
811.531	812.99
826.452	827.98
842.465	Skipped due to double peak
852.144	853.69
912.297	913.66

We calculated an average offset of 1.63 nm from the oceans spectrometer.

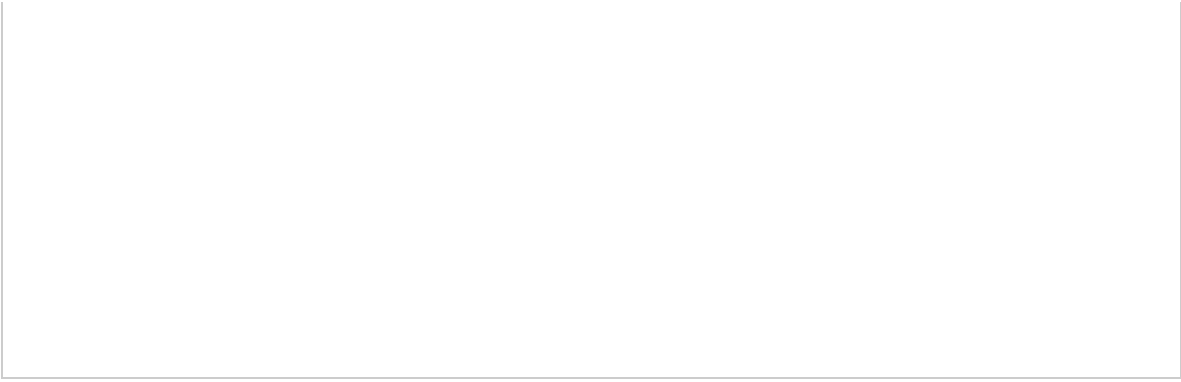


Calibration  
of the oce...



Calibration  
of the oce...

Expected wavelength (nm)	Experimentally calculated wavelength ( )	Difference (nm)
365.02	366.90	-1.88
404.66	406.46	-1.80
407.78	409.60	-1.82
435.83	437.58 - cannot be used as the peak is maxed out.	N/A
546.07	548.48 - cannot be used as the peak is maxed out.	N/A
576.96	578.71	-1.75
579.07	580.72	-1.65
696.54	698.17	-1.63
706.72	708.36	-1.64
710.75	N/A	N/A
727.29	728.82	-1.53
738.39	739.84	-1.45
750.39	751.95	-1.56
763.51	765.11	-1.60
772.38	773.91	-1.53
794.82	796.41	-1.59
800.62	802.69	-2.07
811.53	812.99	-1.46
826.45	827.98	-1.53
842.47	Skipped due to double peak	N/A
852.14	853.69	-1.55
912.30	913.66	-1.36
Average difference (nm)		-1.63



# Using Bulb Calibration

Sunday, 6 February 2022 15:02

- Created this function to find the y value from data even if desired x value is not in data set
  - o This is done by finding the two closest points and interpolating between these two points as a percentage of the way between two said points
- The following function represents this task

```
classdef OpticalAnalysisFunctions
    methods(Static)
        % y True Value
        function y_true_value = nearestValue(x_Store, x, y_Store)

            x_diffs = x-x_Store;

            if isempty(find(x_diffs==0)) == 0
                lowest=find(x_diffs==0);
            elseif isempty(find(x_diffs==0)) == 1
                lowest=max(find(x_diffs>0));
            end

            highest=lowest+1;

            y_diff = y_Store(highest)- y_Store(lowest);

            if y_diff ~= 0
                x_Percentage = x_diffs(lowest)./(x_Store(highest)-x_Store(lowest));
            elseif y_diff == 0
                x_Percentage = 0;
            end

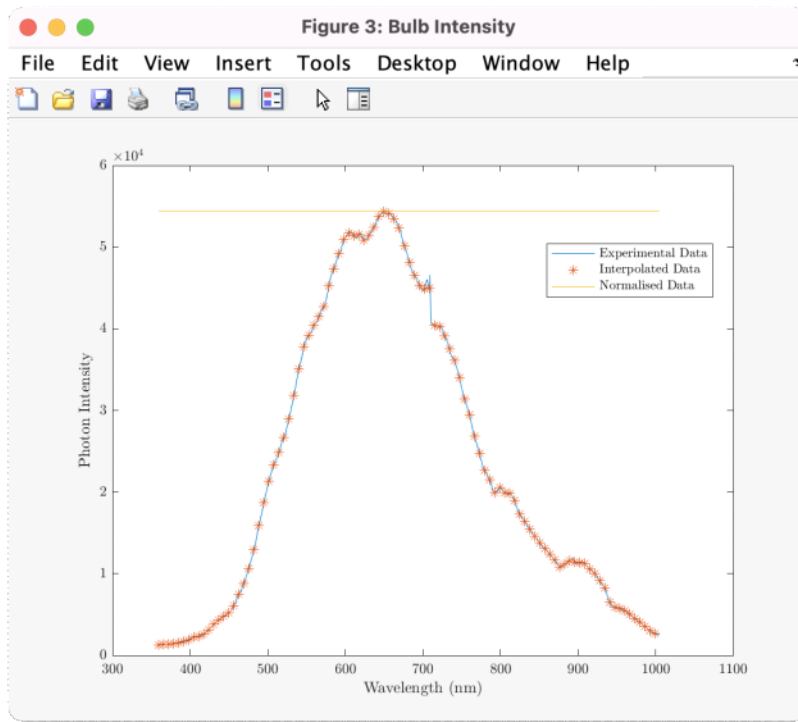
            if y_diff ~= 0
                y_true_value = y_Store(lowest) + (y_diff).* x_Percentage;
            elseif y_diff == 0
                y_true_value = y_Store(lowest);
            else
                disp('Error Alert')
            end
        end
    end
end
```

In the main m file the code:

```
intensitydata = intensitydata(7:end,:);
intensitytest = zeros(size(1000));
wavelength = linspace(min(intensitydata(:,1)), max(intensitydata(:,1)), 1000);
for i=1:max(size(wavelength))
    intensitytest(i) = OpticalAnalysisFunctions.nearestValue(intensitydata(:,1), wavelength(i),
intensitydata(:,2));
end
normalised_intensity = intensitytest.*(max(intensitytest)./intensitytest);
figure('name','Bulb Intensity')
set(groot,'defaultAxesTickLabelInterpreter','latex');
set(groot,'defaulttextinterpreter','latex');
set(groot,'defaultLegendInterpreter','latex');
plot(intensitydata(:,1),intensitydata(:,2))
hold on
plot(wavelength(1:10:end),intensitytest(1:10:end),'*')
hold on
plot(wavelength,normalised_intensity)
xlabel('Wavelength (nm)','Interpreter','latex')
ylabel('Photon Intensity','Interpreter','latex')
legend('Experimental Data','Interpolated Data','Normalised Data',...
'Location','best','Interpreter','latex')
```



Iterated over all wavelengths and produced the following graph.



This demonstrates that the code is fully operational as these are the desired plots

Sunday, 6 February 2022 15:07

- Used the following code:

Said code produced the following graph:



# Day 2 in the lab (edit needed)

Thursday, 3 February 2022 15:25

## Aims:

- Calibrate the monochromator
  - Figure out why we get a double peak
- 
- To prevent the ocean spectrometer maxing out we set the aperture of the Bentham to 0.15 mm.
  - The eye of the spectrometer was slightly miss aligned, when we aligned this better

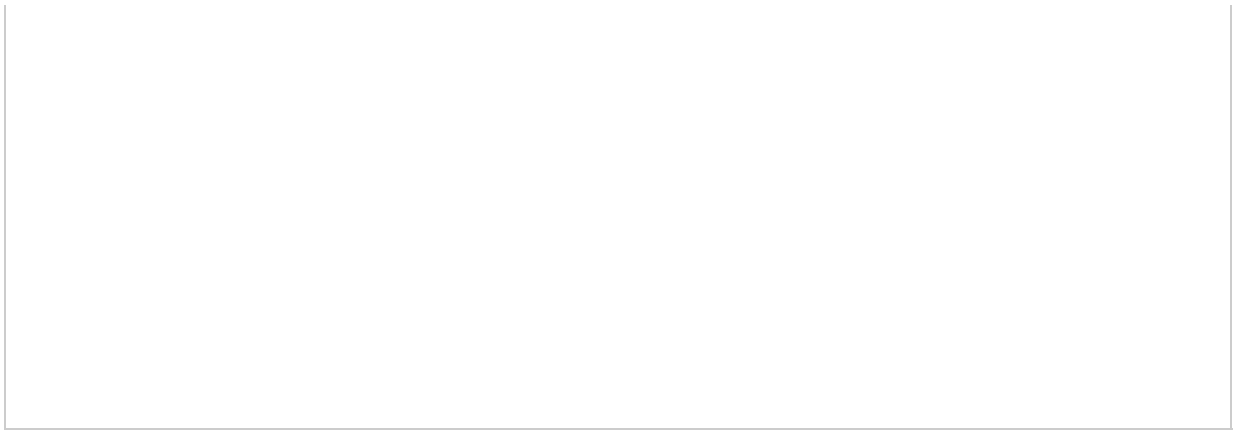


Bentham  
calibration



Bentham  
calibratio...

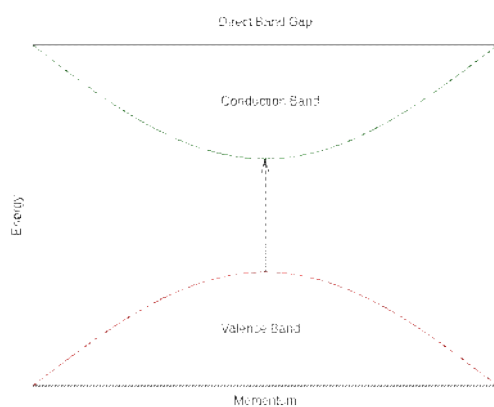
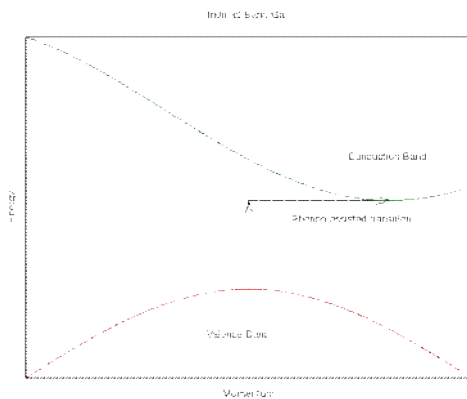
Target wavelength	Ocean optics wavelenght	Calibrated wavelength
500	510.84	509.21
600	609.87	608.24
700	708.94	707.31
800	807.84	806.21
900	906.86	905.23
1000	1005.85	1004.22



# Direct and indirect band gaps

Saturday, 15 January 2022 23:08

- The band gap in a semiconductor can be characterised by either a **direct** or **indirect** band gap.
- The **minimum** energy of the conduction band and the **maximum** energy of the valence band are described in k vector.
- If the k vectors for the conduction and valence band are **different** then it's **indirect** if they are the **same** it's **direct**
- A photon can be directly emitted by a electron in direct band gap but **not** in an indirect one



GaAs represents a direct band gap, GaP represents an indirect band gap <sup>[1]</sup>

<sup>[1]</sup> [https://en.wikipedia.org/wiki/Direct\\_and\\_indirect\\_band\\_gaps](https://en.wikipedia.org/wiki/Direct_and_indirect_band_gaps)

# Band Gap Continued (date change)

Tuesday, 15 March 2022 13:51

- Interactions of photons and phonons between holes and electrons are **necessary for the conservation of momentum** (k vector)
- Around the band gap of semiconductors photons have almost no (zero) momentum
- Two important processes involving the transition of electrons, are carrier generation and recombination. These describe the processes by which an electron moves to the conduction band from the valence band via gaining energy & when an electron loses energy and moves from the conduction band to re-fill the electron hole in the valence band.
  - o Both of these processes must satisfy the conservation of quantised energy and momentum.
- In a direct band gap this is easily done as the minimum of the conduction band and the hole will share the same k vector. Therefore as photons have near to zero momentum, it can be used to promote an electron to the conduction band without effecting the momentum of the 'crystal lattice', which is necessary as the momentum is the same.
- However in an indirect band gap this simple transition is not possible as the minimum of the conduction band and the hole share a different k vector. In order to conserve the momentum of the crystal lattice, there must be either an absorption or emission of a phonon. This satisfies the conservation laws as phonons, unlike photons 'carry' little energy but do have momentum therefore can change the k vector.
- The momentum difference of the conduction to valence band is equal to the momentum of the phonon.
- The direct band gap transition is an efficient process, only involving two particles an electron and a photon, meaning the absorption coefficient is typically high  $\alpha = 10^4 - 10^5 \text{ cm}^{-1}$
- In an indirect band gap, as it is a three particle process involving an extra phonon, the process is less likely to occur within a given time period than its counterpart. The absorption coefficient of which is around  $10^3 \text{ cm}^{-1}$ .
- The absorption coefficient is related to the band-gap by the equation [<sup>\[1\]</sup>](#)
  - o  $(\alpha h\nu)^{1/n} = A(h\nu - E_g)$  (exception reference rest is wikipedia)
- This difference in likelihood is why light emitting and laser diodes are made by direct band gap materials and not indirect band gap ones.[2]
- "The basic process occurring is the emission of a photon when an injected electron (or hole) recombined, so in considering the physics of LEDs, attention is focused on to the possible recombination processes in semiconductors and the way in which the recombination energy is dissipated." – **include more from oxford**
- "In a direct-gap semiconductor the minimum of the conduction band and the maximum of the valence band are both at the same value of k, meaning that transitions such as  $\alpha$  in the figure below require no change in momentum, and all the released energy can be carried away by the low momentum photon. In an indirect band-gap semiconductor, the minimum of the conduction band is not  $k=0$ , so that the transition such as  $\beta$  must involve some other particle to conserve momentum. The other body is usually a phonon, which also carries away some energy, so the transition is non-radiative. Transitions such as  $\gamma$  are likely to be rare as there will be few electrons occupying the high energy  $k=0$  region in the band. [3]

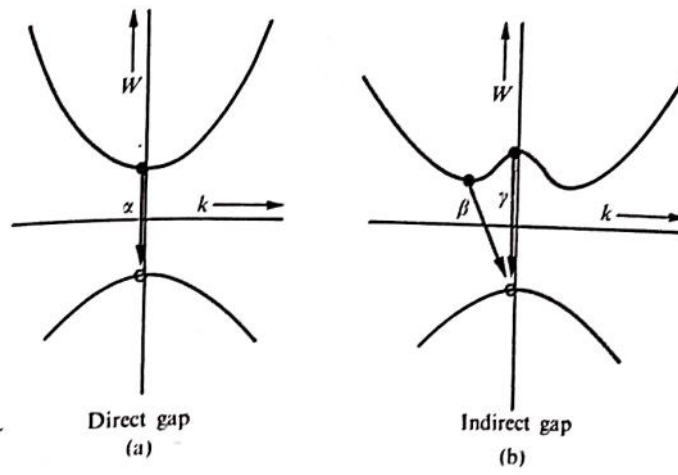


Fig. 3.13. Electron transitions shown on an electron energy versus wave-number diagram for semiconductors having a direct gap and an indirect gap.

[\[1\]](#)Second reference

# Absorption II

Tuesday, 15 March 2022 14:13

- In absorption transmissions between two direct valleys where they are in the same k space.
- Every initial state  $E_i$  is associated with a final state  $E_f$  such that  $E_f = h\nu - |E_i|$ 
  - o In parabolic bands  $E_f - E_g = \frac{h^2 k^2}{2m_e^*}$  and  $E_i = \frac{h^2 k^2}{2m_n^*}$  — is this useless — [5]
- <https://www.researchgate.net/publication/283338024>  
Effect of Se addition on optical and electrical properties of chalcogenide CdSSe thin films
  - o The value for  $E_g$  can be obtained experimentally by use of the Tauc relation, this is given by the equation
    - $\alpha(h\nu) = A(h\nu - E_g)^n$
  - o Where  $\alpha$  is the absorption coefficient which is given by
    - $\alpha = \frac{1}{t} \ln \left( \frac{(1 - R^2)}{T} \right)$
  - o Noting that in the uv range, R may equal to 0 therefore
    - $\alpha = \frac{1}{t} \ln \left( \frac{(1)}{T} \right)$
  - o Where t is the thickness, T and R are the transmission and reflection coefficients respectively
- If a graph of  $(\alpha h\nu)^{\frac{1}{n}}$  versus  $(h\nu)$  is plotted a straight line should be obtained with the x axis being intersected at  $(\alpha h\nu)^{\frac{1}{n}} = 0$ . With the value of  $E_g$  being estimated from this intercept.
- The value of n being dependant on the electronic transition type
  - o  $n=1/2$  — direct allowed transition
  - o  $n=2$  — indirect allowed transition
  - o  $n=3$  — direct forbidden transition
  - o  $n=3/2$  — indirect forbidden transition — dependant on material therefore variable
- The transition type can be determined by the linearity near the absorption edge and which power fit is the best match.
  - o Materially this is determined by how the atomic orbitals are coupled up in the bulk semiconductor.
  - o It is dependant on the material and whether it is crystalline or amorphous and the photon transitions
- **Get appropriate of different transition types**
- An transition between indirect valleys is called an indirect band gap, as it is not a direct one step process but rather an indirect two step process. These two steps are both required as both a change in momentum and energy are needed.
  - o As a photon cannot provide enough momentum (to change the k value enough for the transition to be completed), another interaction is needed. This interaction comes in the form of a phonon which is quantum vibration in the lattice of the material. This phonon can change the momentum which makes this possible transition possible.
    - There are several types of, which include longitudinal and transverse acoustic phonons, both participate in the transitions but with varying probabilities
  - o Each has energy  $E_p$  which is characteristic to that phonon, meaning two processes can completed the transition
    - Emitted —  $h\nu_e = E_f - E_i + E_p$
    - Absorbed —  $h\nu_e = E_f + E_i + E_p$



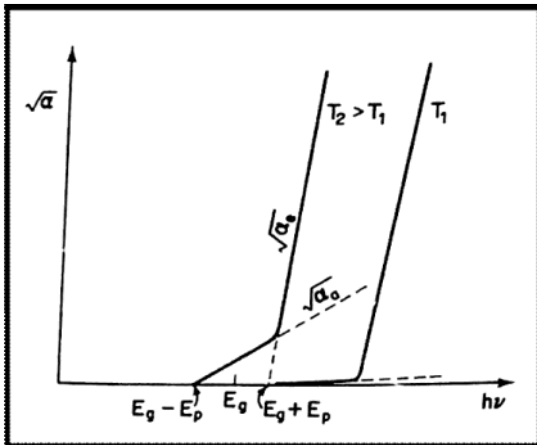
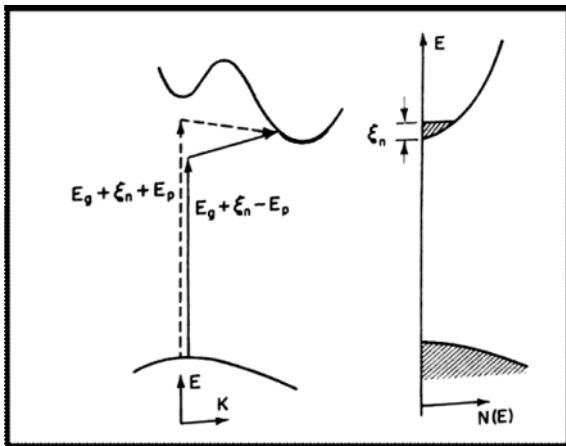
- **Insert picture of transition**

- In these indirect transitions all the occupied states of the valence band can connect to all the empty states of the conduction band
- The absorption coefficient is proportional to the product of the densities of the initial states, it is also proportional to the interacting phonons, which is a function of the phonons energy. With some mathematical manipulation (just go to it straight away?), the absorption coefficient are obtained.

- Phonon absorption —  $\alpha_a(h\nu) = \frac{A(h\nu - E_g + E_p)^2}{e^{-\frac{E_p}{kT}}} = C(E - E_g + E_p)^2, E > E_g - E_p$

- Phonon emission —  $\alpha_e(h\nu) = \frac{A(h\nu - E_g - E_p)^2}{1 - e^{-\frac{E_p}{kT}}} = C(E - E_g - E_p)^2, E > E_g + E_p$  [8]

- Since both phonon absorption and emission are possible when  $h\nu > E_g + E_p$ 
  - $\alpha(h\nu) = \alpha_a(h\nu) + \alpha_e(h\nu)$
- At very low temperatures, the phonon density is very small, therefore  $\alpha_a$
- This temperature dependence is shown on the figure below and illustrates the type of fit we expect to get for our results.



From the graph if extrapolated to  $\alpha = 0$  the values for both  $E_g - E_p$  and  $E_g + E_p$  can be obtained

- If a semiconductor is heavily doped, the fermi level is inside the band, (the conduction band if in an n-type semiconductor) by a quantity  $\xi_n$ , and hence the energy states below  $\xi_n$  are already filled, transitions to states below  $E_g + \xi_n$  are forbidden. Therefore the absorption edge shifts higher.
- A phenomenon which occurs in heavily doped indirect gap semiconductors is the ability to conserve momentum by electron scattering and hence not needing a phonon to do so.
  - $\alpha(h) = A_V(h, -E_g - \xi_n)^2$
- Indirect transitions between direct valleys are also possible and are similar to transitions between indirect valleys, where momentum is conserved via a phonon interaction. Again all the valence band states are connected with empty states in the conduction band.
- Such a transition, being a two stepped process has a lower probability of occurring than a direct transition. The true absorption coefficient would be the sum of the two contributions.
- [5]

- It is well known that the probability of the process decreases with the increasing number of particles participating in it. Therefore light absorption in indirect semiconductors near the absorption edge occurs less intensely compared to direct band gap semiconductors.
- If  $E_g$  is the band gap, it can be concluded that the band gap of a semiconductor can be determined using the relation
  - $E_g = hc/\lambda_{\text{red}}$
- Where  $h$  is the plank's constant,  $c$  is the speed of light,  $\lambda_{\text{red}}$  is the red edge of absorption, where the wavelength which light absorption really occurs.
  - In reality this equation only calculates a rough estimate of  $E_g$ . In reality the energy distribution of energy states differs from that in an ideal crystal, therefore the energy distribution is resembled by 2.b and not 2.a. The reason for this difference are defects in the crystal which create additional fields. The presence of such fields leads to the appearance of these tails of these density of electronic states as shown.
- To determine the band gap energy correctly use the equations with  $\alpha$ .
- 
- [5]

# Urbach (date)

Tuesday, 15 March 2022 13:53

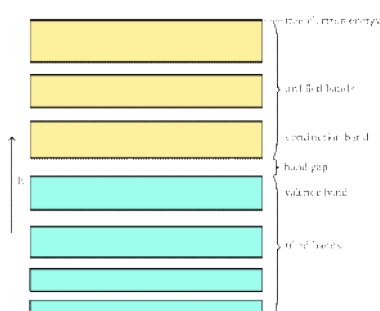
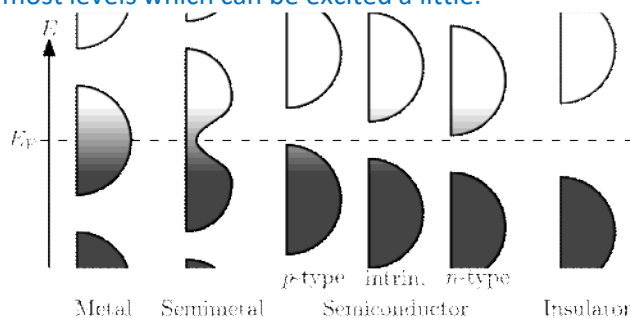
- Urbach energy (EU): Is governed by the structural disorder, imperfection in stoichiometric and passivation at the surface . Urbach energy also indicates the disorder of phonon states in the film. Urbach energy is found below absorption band edge of compound. Urbach energy characterizes the degree of the absorption edge smearing due to the crystalline lattice disordering caused by structural peculiarities as well as induced by external factors. The absorption coefficient at the photon energy below the optical gap (tail absorption) depends exponentially on the photon energy:  $\alpha(\hbar \omega) \sim \exp(-\hbar \omega/E_u)$  where,  $E_u$  is called Urbach energy.
- [https://www.google.co.uk/url?sa=t&rct=j&q=&esrc=s&source=web&cd=20&ved=2ahUKEwjepoWA3vnnAhUOWsAKHcUdDWYQFjATegQIBhAB&url=http%3A%2F%2Fwww.sapub.org%2Fglobal%2Fshowpaperpdf.aspx%3Fdoi%3D10.5923%2Fj.optics.20140403.02&usg=AOvVaw29L1\\_KK70DGjxJf9juKi0I](https://www.google.co.uk/url?sa=t&rct=j&q=&esrc=s&source=web&cd=20&ved=2ahUKEwjepoWA3vnnAhUOWsAKHcUdDWYQFjATegQIBhAB&url=http%3A%2F%2Fwww.sapub.org%2Fglobal%2Fshowpaperpdf.aspx%3Fdoi%3D10.5923%2Fj.optics.20140403.02&usg=AOvVaw29L1_KK70DGjxJf9juKi0I)
- In the region corresponding to the transitions involving the tails of the electronic density states, the dependence of the absorption coefficient  $\alpha$  is described by the Urbach equation
  - o Insert equation
- Where  $\alpha_0$  is a constant,  $E_u$  is the Urbach energy that reflects structural disorder and defectiveness of the semiconductor
- It follows from the equation between  $\alpha$  and  $E_g$  that the slope of  $\ln(\alpha) - h\nu$  dependence is reciprocal to the Urbach energy. Thus, the analysis of the optical absorption in the range corresponding to the tails of the density of states allows us to determine the Urbach energy and thereby classify the degree of material imperfection. [7]

# Band Structure Continued (date)

Tuesday, 15 March 2022 13:53

## Electrons in the band structure [1,3]

- The band structure of the material is determined by which energies are allowed (these allowed energy's are given by wave functions). This is in contrast to the band gaps which are the energies that are forbidden, where electrons cannot reside. The structure of these bands can then tell you about material properties, such as the electrical resistivity and more necessary to this experiment, the optical absorption. Both of which help develop a fundamental understanding for solid state devices such as transistors and solar cells.
- The energy distribution is determined by the fermi level and the temperature of the electrons. At absolute zero in a semiconductor this practically means that all the band gaps below the band gap are filled and all the states above which are empty.
- However at a given finite temperature electrons begin to be excited into higher energy levels, which are free states above the conduction band. The electrons can only jump over the band gap as all the energy states below the bad gap are filled and due to the Pauli exclusion principle only one electron may occupy a given energy level. [1]
- **Refer to figures!!!! Also hyper physics!!!!**
- In a solid each electron within that, has a finite determinable energy, which is made up of both kinetic and potential energy. Within a given metal there will be ranges of energies where the electron can be found, and others where there are no electrons.
  - o Forbidden band – no electrons have these energies
  - o Allowed bands – there may be electrons at these energies
- Typically the lower bands will all be full of electrons and the higher ones empty.
- Forbidden energy bands are due to:
  - o Electrons having a wavelike nature
  - o This results in only suitable solutions with a certain values being allowed, as a result of the wave equations.
  - o The quantum number dictating which state the electron has to occupy
  - o The arrangement of atoms in crystals leads to electron states having energies only with certain ranges. [3]
- At absolute zero the electrons would go to the lowest energy state possible. At room temperature, when there is a little more energy in the system, there's a small proportion of electrons in the uppermost levels which can be excited a little.



# Bond Model

Tuesday, 15 March 2022 13:54

- Most semiconductors are made from crystals. Despite there being a multitude of ways in which the atoms can be internally arranged, almost all important semiconductors have the same crystal structure, which is that of diamond.
- As a consequence of this structure is that its isotropic and therefore has the same physical properties in all directions (and the same values for those properties)

# Introduction to Project (date 1st)

Tuesday, 15 March 2022 14:05

- There are different mechanisms of light absorption by semiconductors: interband (fundamental absorption), dopant absorption, excitonic absorption, absorption by free charge carriers, absorption by crystalline lattice. The fundamental absorption is the one which leads to the generation of electron-hole pairs as a result of optical excitation of electrons from the valence band to the conduction band. Which will be the absorption which dictates this experiment.
- The laws of physics must be obeyed and therefore the process of light absorption must adhere to the conservation of both momentum and energy.
  - This in particular leads to the fact that the minimum energy sufficient for an electron to be excited to the conduction band from the valence band, is equal to the band gap of the semiconductor in question. — this relates to direct band gap
  - In addition this also leads us to the conduction and valence need to coincide in the same  $k$  vector, or have a interaction which maintains the conservation of momentum. This is where phonon interaction comes into play
  - “It’s noted that the wavelength of visible light is about three orders of magnitude larger than the lattice parameter. Accordingly, the photon wave vector is about three orders of magnitudes smaller than the size of the first Brillouin zone. Therefore, with a high degree of accuracy we may assume that absorption of a photon of visible light does not change the momentum of the electron.”

Source:

# Uses of semiconductors

Tuesday, 15 March 2022 14:06

- Solar Cells
  - The difference of intensity of light absorption in direct vs indirect band gaps is of great importance, in particular, in relation to solar cell technology. In the case of direct band gap semiconductors, it is sufficient to use only a few absorbing layers with a thickness of a few micrometres in addition to the material quality being relatively low.
  - On the other hand for an indirect band gap semiconductor, such as silicon, to be used in the production and manufacturing of solar cells, it is necessary to use thick layers (in the order of a few hundred micrometres) to ensure the sunlight is absorbed effectively. This leads to an increase in material consumption, as well as a increased quality of material comparatively.
  - "It is precisely for this reason that the lowest cost of generated photovoltaic energy is achieved to date by using thin film solar cells based on direct band gap materials (CdTe, First Solar company, USA)"

# Fundamental Absorption I

Tuesday, 15 March 2022 14:07

- The simplest and most direct method for determining the band structure within a semiconductor, would be to measure the absorption spectrum. This is done by studying the change in the transmission spectrum when the material is placed in front of monochromatic light. Thus by seeing the changes, the possible transitions can be determined which tell you the distribution of the energy states.
- "Absorption is expressed in terms of a coefficient  $\alpha(h\nu)$  which is defined as the relative rate of decrease in light intensity  $L(h\nu)$  along its propagation path"
  - $\alpha = \frac{1}{L(h\nu)} \frac{d[L(h\nu)]}{dx}$
- Fundamental absorption refers to the excitation of an electron from one band to another (valence to the conduction band).
  - This process can be used to calculate the energy gap in the semiconductor between the bands.
- Despite the seeming simplicity of absorption there are a number of possible transitions which can be taken and which one is taken depends mainly on the conservation of momentum and energy.

Source : panvok book



# Absorption III

Thursday, 17 March 2022 11:28

Some handwritten rough notes relating to fundamental absorption



new doc  
2-2



new doc  
3-2

$$\alpha(h\nu) = A(h\nu - E_g)^n$$

$$\alpha(h\nu) = A(h\nu - E_g)^{1/2}$$

$$\therefore \alpha^2(h\nu) = A^2(h\nu - E_g)$$

$$\therefore \alpha^2(h\nu) = \overset{\uparrow}{A^2} \overset{\uparrow}{h\nu} - \overset{\uparrow}{A^2} E_g$$

y                      x                      c.

$$\therefore \alpha^2(h\nu) \propto h\nu - E_g$$

$$\therefore \text{when } y(\alpha^2) = 0$$

$$\therefore h\nu = E_g$$

$n = \frac{1}{2}$  as it's a direct allowed transition

---

Plot of  $\alpha^2$  vs  $h\nu$  yields an x intercept of  $E_g$

---

$\alpha^2$  is plotted not  $\alpha^{1/2}$

---

$$\alpha(h\nu) = A(h\nu - E_g)^n$$

$$\alpha(h\nu) = A(h\nu - E_g)^{1/2}$$

$$\therefore \alpha^2(h\nu) = A^2(h\nu - E_g)$$

$n = \frac{1}{2}$  as it's a direct allowed transition

$$\therefore \alpha^2(h\nu) = A^2 h\nu - A^2 E_g$$

↑  
y

↑  
x

↑  
c.

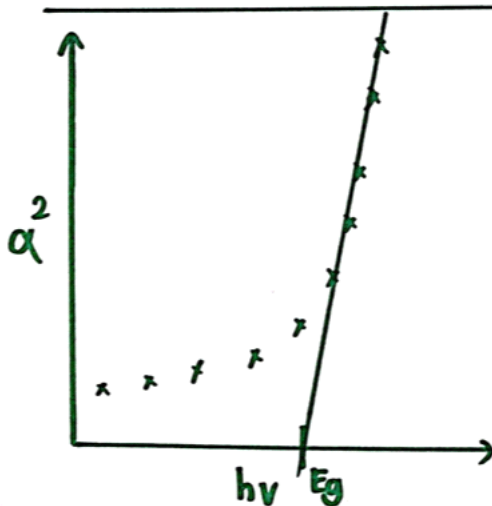
Plot of  $\alpha^2$  vs  $h\nu$  yields an x intercept of  $E_g$

$$\therefore \alpha^2(h\nu) \propto h\nu - E_g$$

$$\therefore \text{when } y(\alpha^2) = 0$$

$$\therefore h\nu = E_g$$

$\alpha^2$  is plotted not  $\alpha^{1/2}$



— Extrapolate the straight section of the graph to create a straight line.

— Intercept is  $E_g$  on x axis

# Imaginary refractive index

Thursday, 17 March 2022 11:34

## Question: Imaginary part of semiconductors index of refraction

The index of refraction is complex and can be expressed as such:  $\tilde{\eta} = \eta + i\kappa$ . However I am unable to find the derivation of why the imaginary part of the refractive index in semiconductors is as follows

$$\kappa = \frac{\lambda\alpha}{4\pi}$$

## Solution:

If  $\alpha$  is the attenuation coefficient, such that  $|E|^2 \propto e^{-\alpha x}$  it is, by pure identification, the definition of  $\alpha$ . Let's write:

$$E = E_0 e^{i(n+ik)k_0 x}$$

where  $k_0 = \frac{2\pi}{\lambda}$  is the vacuum wave number. You get then:

$$E = E_0 e^{ink_0 x} e^{-kk_0 x}$$

and

$$|E|^2 = |E_0|^2 e^{-2kk_0 x}$$

$$\text{Hence } \alpha = 2kk_0 = \frac{4\pi\kappa}{\lambda}$$

# Derivation of Optical Absorption Coefficient

Thursday, 17 March 2022 11:45

## Question:

The absorption coefficient can be expressed as such

$$\alpha = A(hf - E_g)^n$$

with  $n = \frac{1}{2}$  and  $n = 2$  for direct band gap and indirect band gap respectively. I have seen a few explanations via use of effective mass and momentum to infer this, but they all seem to take big steps with no clear and logical explanation.

## Solution:

Starting with parabolic bands. The absorbed photon has energy  $h\nu$  and generates an electronic and hole at energy levels  $E_2$  and  $E_1$  respectively. Energy and moment balance imply,

$$h\nu = E_2 - E_1 = E_c(k) - E_v(k)$$

where  $k$  is the momentum of the photo-generated electron and hole (it's the same for both carriers),  $m_c$  and  $m_v$  are the conduction and valence band effective masses,

$$E_c(k) = E_g + \frac{\hbar^2 k^2}{2m_c}$$

$$E_v(k) = -\frac{\hbar^2 k^2}{2m_v}$$

Solving these for  $k$ ,

$$k^2 = \frac{2m_r}{\hbar^2} (h\nu - E_g)$$

the reduced effective mass is defined as,

$$\frac{1}{m_r} = \frac{1}{m_c} + \frac{1}{m_v}$$

The parabolic bands define the density of states of conduction  $\rho_c(E) \propto (E - E_g)^{\frac{1}{2}}$  and valence  $\rho_v(E)$  bands, however, not all of these states can couple to a photon of energy  $h\nu$ , only states which conserve both energy and momentum.

We need to know the \*\*optical joint density of states\*\*  $\rho(\nu)$  which determines the electronic states which are coupled by a photon of energy  $h\nu$ .

There are a number of ways for deriving this. The simplest is relating an infinitesimal change in conduction band density of states at the electron energy to a infinitesimal change in joint optical density of states at the photon energy,

$$\rho_c(E_2)dE_2 = \rho(\nu)d\nu$$

$$\rho(\nu) = \frac{dE_2}{d\nu} \rho_c(E)$$

Therefore you end up with the joint optical density of states being proportional to,

$$\rho(\nu) \propto (h\nu - E_g)^{\frac{1}{2}}$$

The linear absorption coefficient  $\alpha$  is going to be proportional to joint optical density of states, so

$$\alpha = A (h\nu - E_g)^{\frac{1}{2}}$$

The derivation for indirect semiconductors is much the same but phonons must be included to conserve momentum. This accounts for different exponents.

Before

After

Electron  $E_f$

$+ h\nu$

$E_i$

initial energy

$$= \frac{\hbar^2 k^2}{2m_v^*} + h\nu = \frac{\hbar^2 k^2}{2m_e^*} + \frac{\hbar^2 k^2}{2m_h^*}$$

$$E_f - E_g = \frac{\hbar^2 k^2}{2m_e^*}$$


---


$$E_f - E_g = \frac{\hbar^2 k^2}{2m_e^*} \quad E_i = \frac{\hbar^2 k^2}{2m_h^*}$$

$$E_f = h\nu - |E_i|$$

$$\Rightarrow \frac{\hbar^2 k^2}{2m_e^*} = h\nu - \left| \frac{\hbar^2 k^2}{2m_h^*} \right| - E_g = \frac{\hbar^2 k^2}{2m_e^*}$$

$$\Rightarrow h\nu - E_g = \hbar^2 k^2 \left[ \frac{1}{2} + \frac{1}{2} \right]$$

$$\frac{1}{2m_e} \rightarrow \hbar\omega - E_g = \frac{\hbar^2 k^2}{2} \left[ \frac{1}{m_h^*} + \frac{1}{m_e^*} \right]$$



CamScanner  
r 03-17-2...

## Previous Similar Experiments Structure

Thursday, 17 March 2022 12:58



CamScanner  
r 03-17-2...

### Recorded

- $V_0$  was recorded (1 matrix)
- $V_1$  was recorded (1 matrix)
- $T$  was calculated (matrix) vs  $\lambda$
- $\uparrow T = \textcircled{V_1} \leftarrow$  is this right.

—  $R = \left[ \frac{n-1}{n+1} \right]^2 \leftarrow$  what values of  $n$  to use.

— Use for  $\frac{1-T}{T+1}$   $\swarrow$  2 or 8

$$\alpha = -x^{-1} \ln \left( \frac{[(1-k)^4 + 4T^2 k^2]^{\frac{1}{2}} - (1-k)^2}{2TR^2} \right)$$

How to calculate  $R$ .



# Rough Work on Paper

Thursday, 17 March 2022 13:05

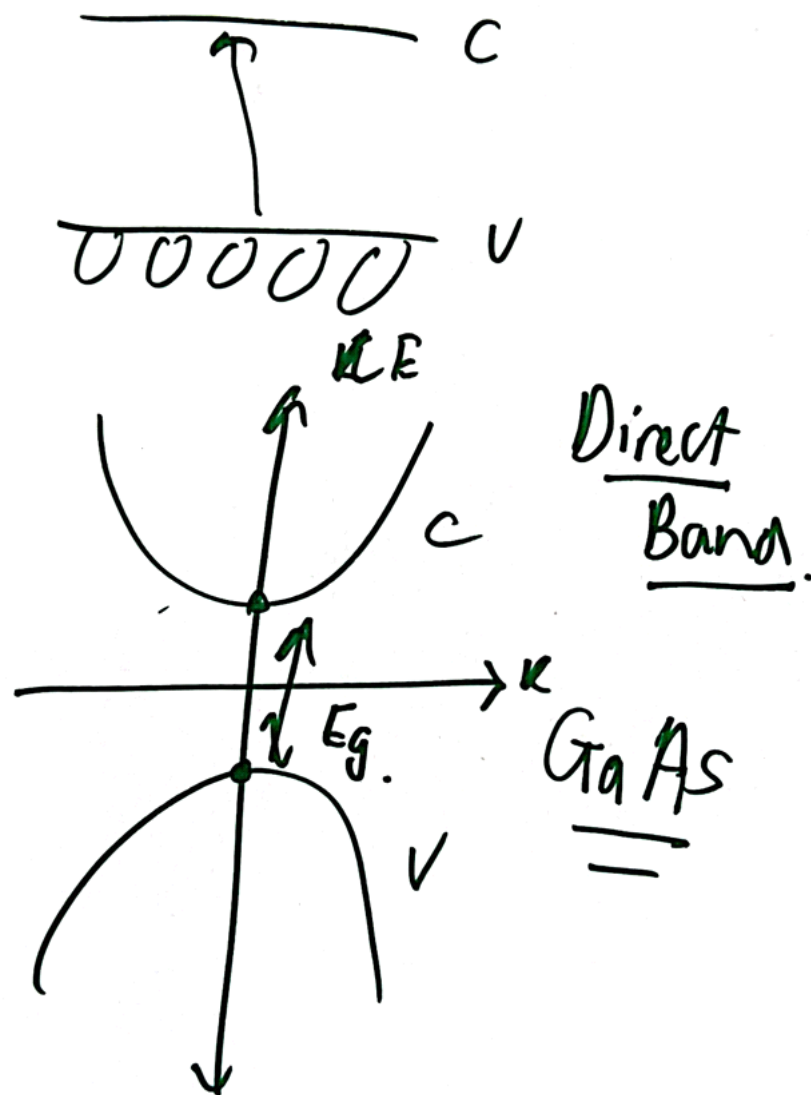


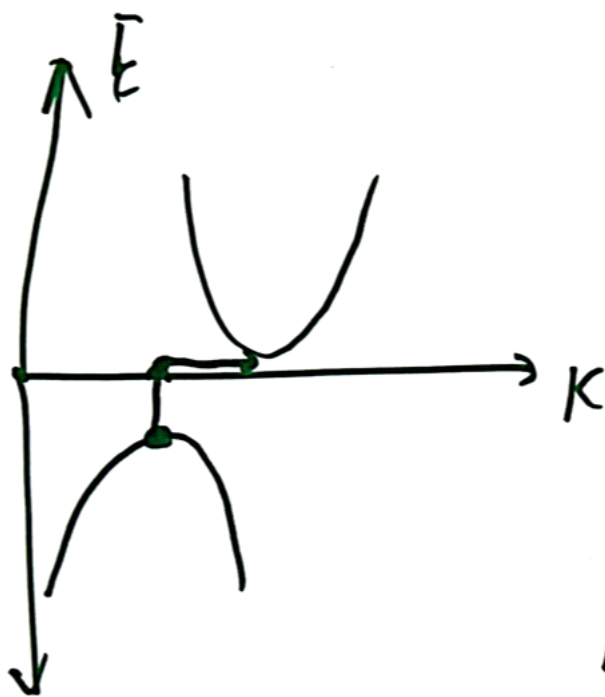
Rough\_Notes



Another\_Set\_Notes

- Here is a small collection of useful rough calculations and explanations of the physics relating to semiconductors - mainly via diagrams



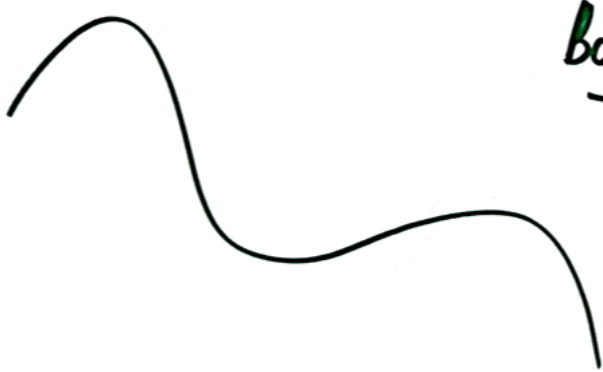


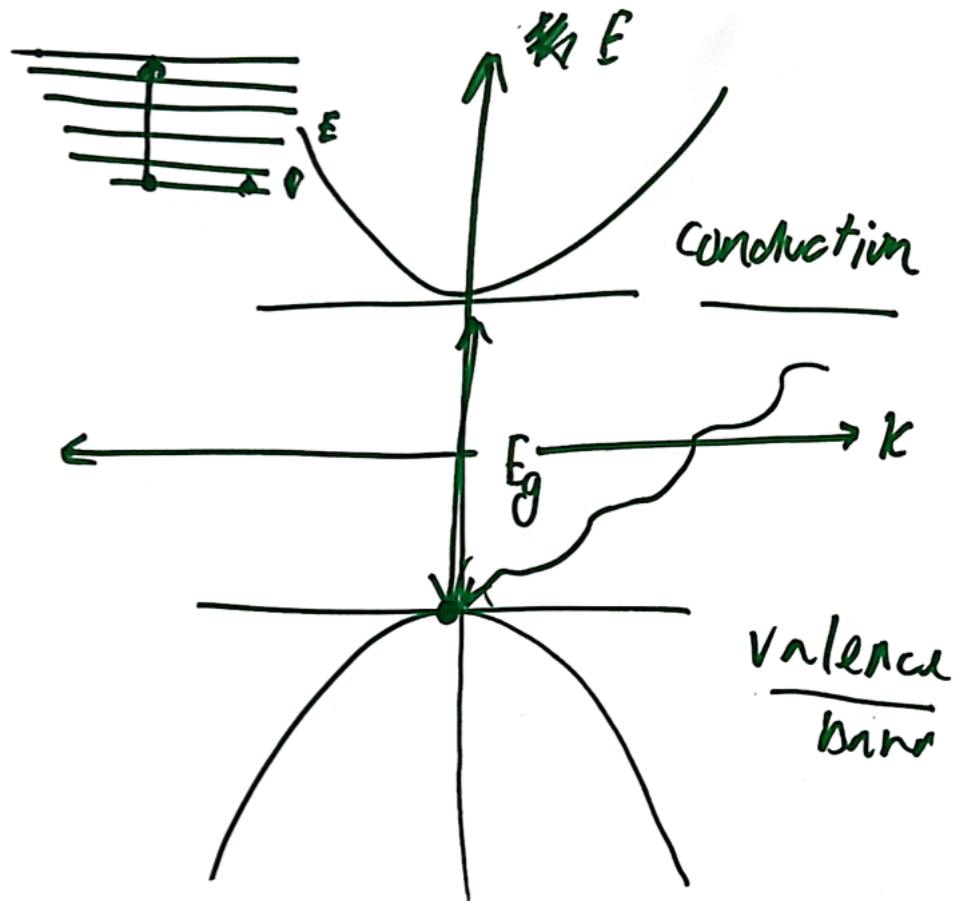
Gap

Photon  $\uparrow E \downarrow p$

Phonon  $\downarrow E \uparrow p$

Indirect  
Band Gap





Meta l



Semi-metal



Semiconductor



$$E = hf \equiv \frac{hc}{\lambda}$$



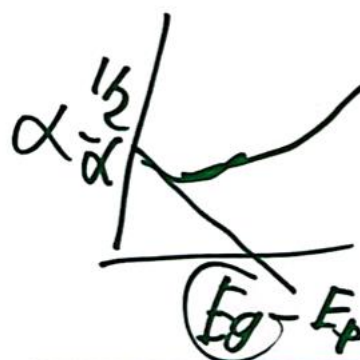
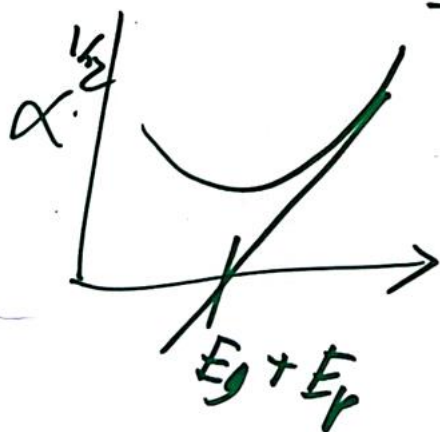
$\alpha =$

$$\alpha(h\nu) = A(h\nu - E_g)^n$$

$n = \frac{1}{2}$

$n = 2$

$\alpha^{1/2}$



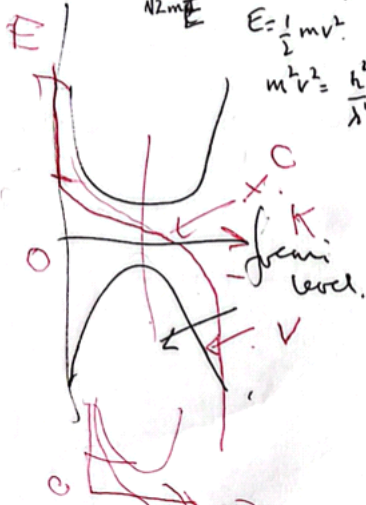
momentum of electron

$$= mv$$

$$\lambda = h \Rightarrow 2mE = \frac{h^2}{\lambda^2}$$

$$E = \frac{1}{2}mv^2$$

$$m^2v^2 = \frac{h^2}{\lambda^2}$$

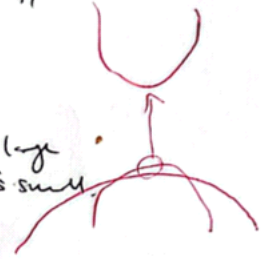


momentum of photon ( $p$ )

$$= mv \text{ (but } v = c)$$

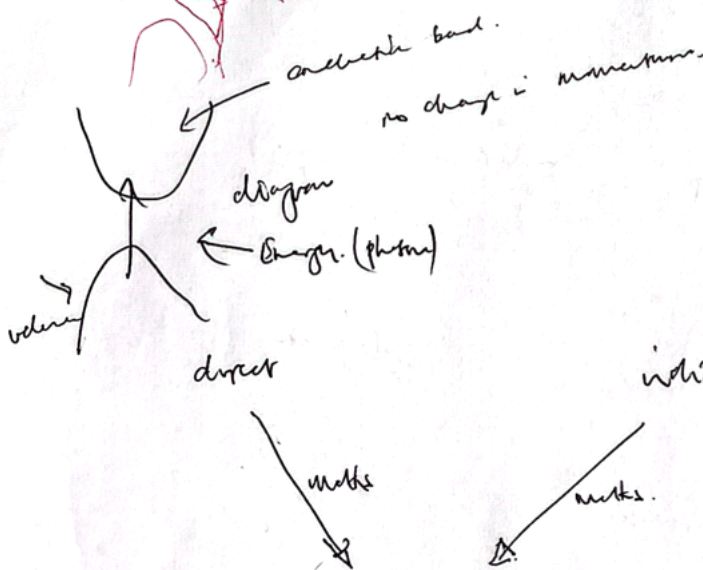
$$= mc \cdot \text{mass} = \frac{h}{\lambda c}$$

$$\therefore p = \frac{h}{\lambda} \therefore \text{if } \lambda \text{ is large } p \approx \text{small}$$



(explains where the probability of absorption are to start with.)

must have conservation of energy and momentum



$\propto$  absorption coefficient

(for which need to calculate T and R)





fermi level.  $\gamma$

fermi function.

absorption of light

direct band gap

indirect band gap

momentum

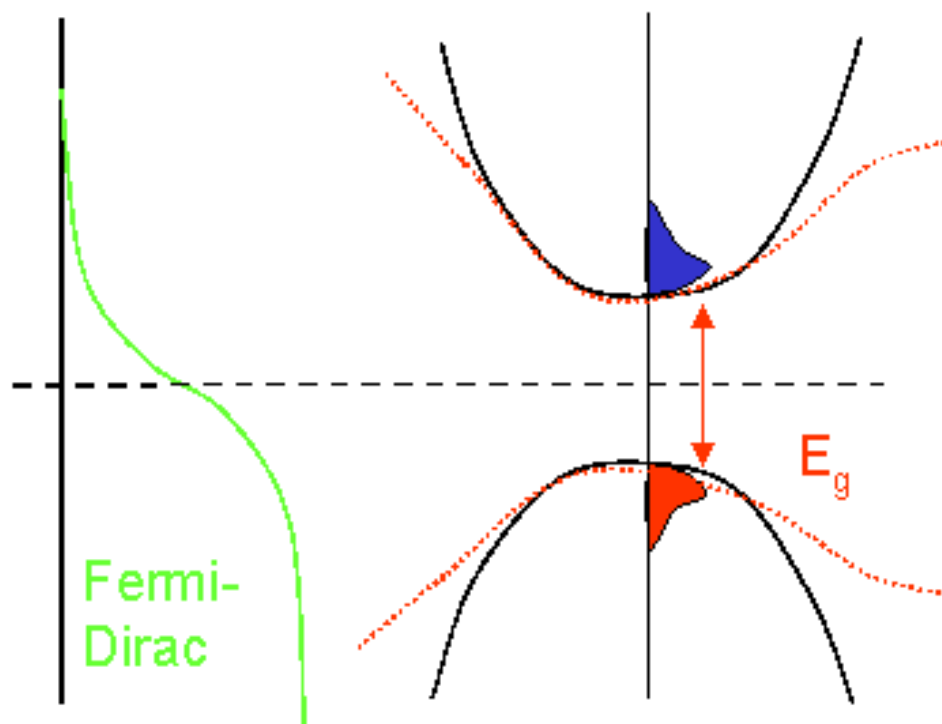
Urbach

conservation of energy.

# Parabolic band approximation

Tuesday, 15 March 2022 13:54

- The fermi level is a chemical potential and refers to the highest electron level, as there are no electron levels within the gap of ideal semiconductors there fermi level would always be at the edge of the valence band
- As shown the conduction and valence band only overlap with the **tails of the distribution**.
- For energies away from the band gap the distribution drops off exponentially, meaning those energy states are hardly ever populated.
- "This allows us to ignore the exact band structure of the material but allows us to expand the energy dependence in Taylor series of second order in  $k$  around the valence band maximum and the conduction band minimum respectively. Meaning the parabolic band approximation can be used."<sup>3</sup>





# Transmission

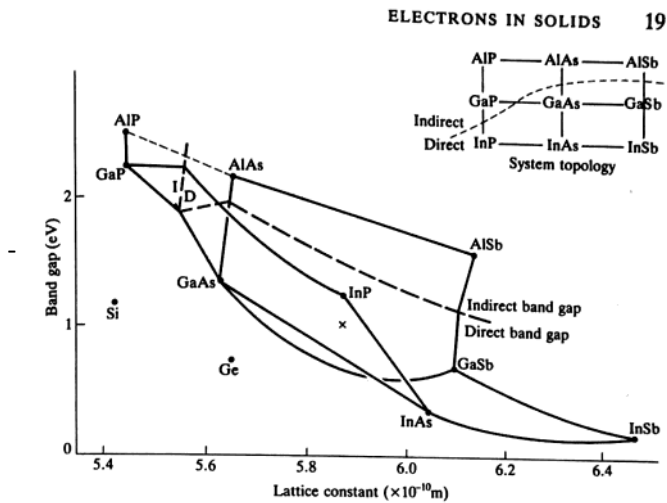
Tuesday, 15 March 2022 14:15

- The transmission coefficient is defined as the ratio of transmitted to incident power,  $\frac{I}{I_0}$ . If the specimen has thickness  $x$ , an absorption  $\alpha$  and a reflectivity  $R$ , the radiation passing through the first boundary is  $(1 - R)I_0$ , the radiation reaching the second boundary is  $(1 - R)e^{-\alpha x}$ , therefore  $(1 - R)^2 I_0 e^{-\alpha x}$  emerges on the other side of the material. Despite the radiation that was internally reflected eventually coming out, it is considerably attenuated.
  - The overall transmission is then given by the fraction of emerged radiation over total radiation.
    - $T = \frac{(1 - R)^2 e^{-\alpha x}}{1 - R^2 e^{-2\alpha x}}$  [5]
      - Where we neglect the spectral dependence of the reflection coefficient [7]
    - $R = (1 - T)/(1 + T)$ 
      - The optical reflection coefficient  $R$  can be determined from the value of a transmission for the transparency region where  $\alpha$  is 0. [7]
  - When the product of  $\alpha x$ , one can neglect the second term in the denominator
    - $T \approx (1 - R)^2 e^{-\alpha x}$
  
- The absorption coefficient for the medium,  $k$ , is defined as
  - $\alpha = \frac{4\pi k}{\lambda} \therefore k = \frac{\lambda \alpha}{4\pi}$ 
    - Where  $\alpha$  is the absorption coefficient, and  $\lambda$  is the wavelength in free space
- In the case of non-absorbing media the expressions for  $R$  and  $T$  are real. Therefore for the normal incidence of an interface between media of indices  $n_1$  and  $n_2$  the expressions are:
  - $R = \frac{(n_2 - n_1)^2}{(n_2 + n_1)^2}$
  - $T = \frac{4n_2 n_1}{(n_2 + n_1)^2}$
- For a case which is a reflection normal to the conducting surface, where in the case of this experiment, where the first medium with air is  $N = 1$ , and the second medium  $N'' = n - ik$ , the equation for the reflectivity coefficient above is valid and gives:
  - $R = \frac{(n - ik - 1)^2}{(n - ik + 1)^2}$  which can be simplified to  $R = \frac{(n - 1)^2 + k^2}{(n + 1)^2 + k^2} \approx \left[ \frac{n - 1}{n + 1} \right]^2$
- The assumptions above are valid as :
  - The reflective index is complex and may be expressed as
    - $N = n + ik$
  - Considering  $k \leq \frac{10^{-2}}{4n} = 10^{-3}$ . Since  $n \approx 3.3$  for GaAs and GaP, the approximation made above is clearly valid. [8]

## 3 – 5 Semiconductors

Tuesday, 15 March 2022 13:55

- Si and Ge both of group IV have a diamond structure due to the amount of electrons free in its outmost shell



# Bulk Effects

Tuesday, 15 March 2022 13:55

- Most semiconductor devices exploit the properties of interfaces, there are a number of uses to which a uniform block of semiconductor can be put.

# References

Tuesday, 15 March 2022 13:55

- List of references where I garnered some information - just keeping track of where I obtain information

1. [Direct and indirect band gaps](#) – Includes links within this page!!!!
  - a. Direct and indirect band gaps
2. [Optical spectroscopies](#)
  - a. Fill in
3. Electrons in the band structure superstate
  - a. Parabolic band approximation
4. Oxford - [Oxford.pdf](#)
  - a. The band model
  - b. Energy bands
  - c. 3-5 semiconductors
  - d. Bulk effects
5. Panvok - [pankove.pdf](#)
  - a. Fundamental absorption
  - b. Direct and Indirect band gaps
  - c. Transmission
6. Moss - [moss.pdf](#)
7. Book
8. “Tempus” “Belarusian state university” “study of semiconductors” – Also 7!!!!
  - a. Methods of absorption
  - b. Introduction
  - c. Uses
  - d. Direct and Indirect band gaps
  - e. Adsorption
  - f. Transmission
  - g. Reflection
  - h. Urbach
9. Paper 1
10. Paper 2

# Band Structure

Saturday, 15 January 2022 23:27

## Electrons in the band structure [1,3]

- The band structure of the material is determined by which energies are allowed (these allowed energy's are given by wave functions). This is in contrast to the band gaps which are the energies that are forbidden, where electrons cannot reside. The structure of these bands can then tell you about material properties, such as the electrical resistivity and more necessary to this experiment, the optical absorption. Both of which help develop a fundamental understanding for solid state devices such as transistors and solar cells.
- The energy distribution is determined by the fermi level and the temperature of the electrons. At absolute zero in a semiconductor this practically means that all the band gaps below the band gap are filled and all the states above which are empty.

# Given Paper

Sunday, 16 January 2022 01:27

- The optical transmission data for a bulk semiconductor sample is calculated
- Then a simple manipulation of the data yields the absorption coefficient  $\alpha$  for the semiconductor
  - o This is specifically in the energy range near its absorption edge
- It is showing that a model based on the direct optical transition describes the data from the GEAS sample and a model based on the indirect optical transition involving a single photon accurately describes the data taken from the GAP sample.
- It's a shame that the data is consistent with the model of
- It's a shame that the data is consistent with a model based on the direct optical transition involving exponential Band tail states
- Calculation of both the energy gap and the back slope is essential
- The simplest way to measure the band structure of a semiconductor is to measure the optical absorption spectrum
- In the absorption process a photon with known energy excites an electron from lower to higher energy state within the semiconductor
  - o From this data much is learnt about the distribution of allowed electronic energy levels
- A bulk semiconductor's optical absorption coefficient  $\alpha$  can be directly calculated from the article transmission data.
- When light intensity  $I_0$  at wavelength  $\lambda$  is incident on a semiconductor wafer of thickness  $x$  the transmitted intensity emerges on the opposite face.
- The transmission coefficient  $T$  is given by  $I_0/I$ .
- Insert equation of  $T$
- Nearest band edge the imaginary part of the semiconductor's index or a fraction  $K$  equals  $\lambda \alpha$  over to  $4\pi$  is much smaller than the real part.
- Insert equation of  $R$  and approximation
- Find out range of  $\alpha$
- Find out range of  $\lambda$
- Find out refractive index
- Find out how the approximation of  $K$  is made
  - o If  $K$  is low the approximation is valid
- The dominant mechanism for optical absorption in the semiconductor of bandgap  $E_g$  is valence band to conduction band electronic transition.
- Assume parabolic bands and justify
- Look at picture of experiment
- If a photon of energy  $E$  directly creates an electron pair of energy  $E_g$  and coefficient is given by and equals half
  - o  $\alpha$  depends only on material properties
- In direct gap semiconductors disorder due to impurities and temperature effects will cause exponential band tails of electronic states to extend into semiconductors for forbidden gap.
- Near the absorption edge optical transmissions from a parabolic band to an exponential Bandtail state and manifested by exponentially varying absorption coefficient
  - o  $\alpha = B \exp(-E/E_g)$ 
    - $B$  is a constant and easier it is Urbach, a parameter describing the steepness of the exponential bandtail.
- If a photon of energy  $E_p$  is required to conserve momentum in the optical production of an Electron-Hole Pair (EHP) as the band edge is an indirect semiconductor assuming parabolic bands
  - o Insert equation relating photon energy  $E_p$  to  $E_g$

# Paper 2

Sunday, 16 January 2022 03:05

- Hey simple experiment to determine the complex refractive index of a semiconductor in thin-film form through transmission measurement is presented.
- And energy dependence analysis of  $\alpha$  is done to obtain the semiconductor bandgap valley and the nature of the optical transmission (direct or indirect).
- A complete optical characterisation of a semiconductor both in bulk and in thin film is possible by measuring the complex refractive index,  $N = N' - jK$  the real part of the refractive index  $N'$  is related to important physical properties of the semiconductor for example reflecting spectrum which in turn is connected with the band structure.
  - o Also the knowledge of the parameter is important for thin-film semiconductor practical applications such as multi layer structures and anti reflective coatings.
- The complex part the refractive index case is directly related to the absorption of coefficient  $\alpha$  by means of the simple expression,  $\alpha = 4\pi K/\lambda$
- 1
  - o Direct gap semiconductor
- 2
  - o Indirect gap semiconductor
- 3
  - o If  $E_p \ll E_g$
  - o Where e.g. is the bandgap Valley  $E_p$  is the photon energy involved in the indirect transitions and  $B$  is a constant.
- This experimental method is precise enough not only to determine the bandgap value but also to determine the nature of the optical transitions i.e. whether it is in direct or indirect band gap.
- Insert known a question related to  $R$ .
  - o Transmittance can only be measured on an extremely thin sample given the  $\alpha$  values for typical semiconductors are in the region of  $10^3$  to  $10^4$  cm range fortunately thin-film semiconductors of thickness of about one micro meter are commonplace.
- Remember to quote where you got the refractive index from that's very key.

# Abstract

Tuesday, 15 March 2022 13:58



# Introduction

Tuesday, 15 March 2022 13:59

# Experimental Method

Tuesday, 15 March 2022 13:59

# Results

Tuesday, 15 March 2022 16:07

# Discussion

Tuesday, 15 March 2022 16:07

# Conclusion

Tuesday, 15 March 2022 16:08

# Planning

Thursday, 17 March 2022 12:56



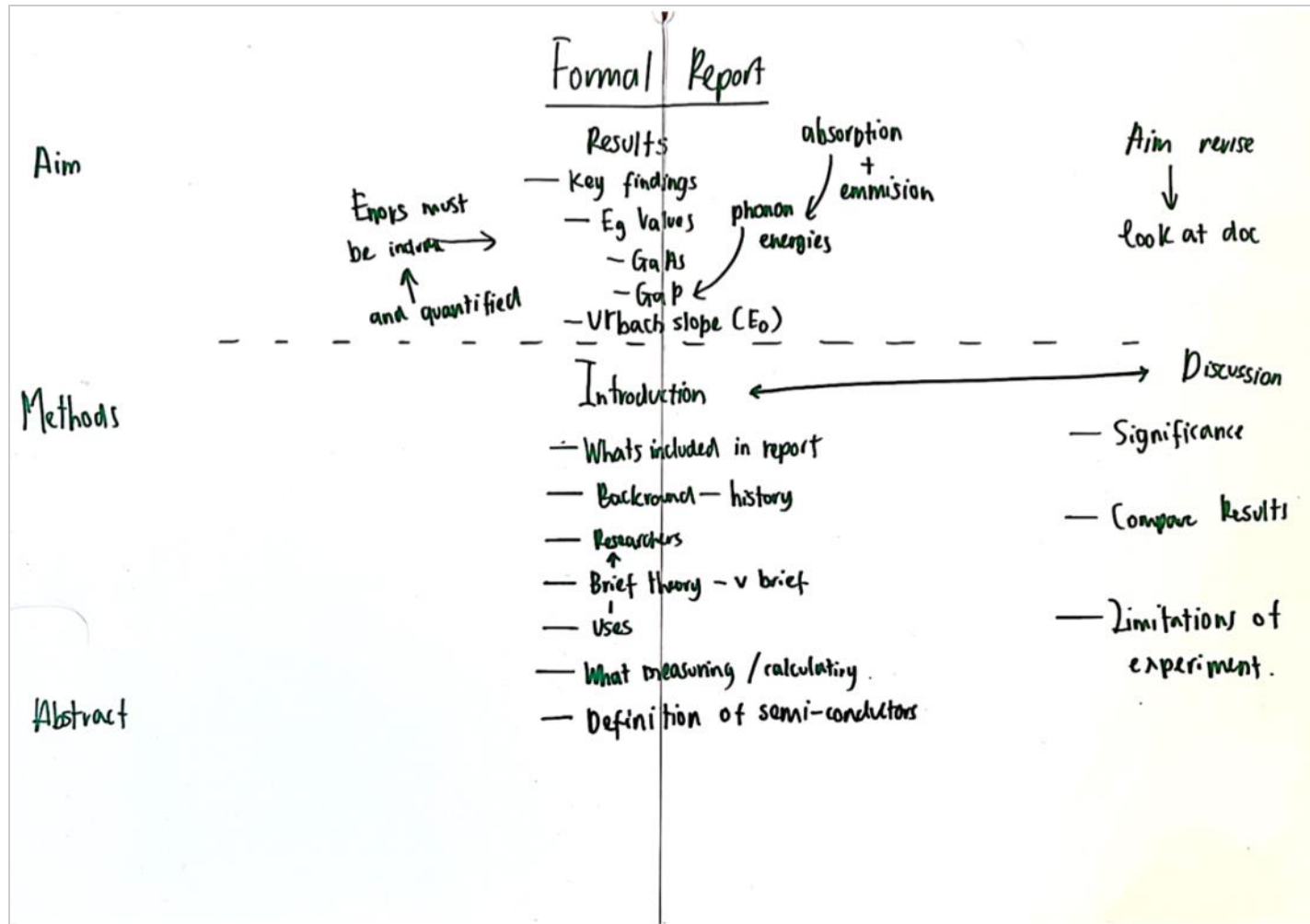
Detailed\_A  
3\_Plan



Rough\_Plan  
\_A4






Semidetailed  
Structure




# Theory Order

C+V band

- 250 — Physics of semi-conductor
- 200 — Energy Bands and Band structure
- 100 — Absorption brief - types
- 250 — Carrier Generation and recombination
- 250 — Transmission and Reflection
- 200 — Direct } band gap
- 200 — Indirect }
- 250 — Absorption — related to  $E_g$  and band gap
- 50  Parabolic Band approximation ← flexible
- 50  Bulk effects
- 50  3-5 semiconductors ← band model
- 100 — Urbach slope

## Introduction

- History
- Intro to Physics
- Uses
- Tie in experimentally

$$F \propto x \quad F = kx + c$$


## Formal Report Structure

### Theory

$$V_0 = 1.854$$

$$V_1 = 1.393$$

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

$$\alpha_n^{1/2} = C^{1/2} (E - E_g + E_p)$$

$$\frac{\alpha_n^{1/2}}{C^{1/2}} = E - E_g + E_p$$

$$\frac{\alpha_n^{1/2}}{C^{1/2}} = E + y$$

$$E_g - E_p = 2.0671$$

$$E_g + E_p = 2.152$$

$$E_g = 2.10805$$

$$E_p = 0.04395$$



# Questions for Henini

Tuesday, 4 January 2022 13:32

- Do we require any sample preparation.
- Why do we not require the lock-in.
- Urbach tail in direct and indirect semiconductors:
  - o Specifically what these tails look like on graphs and how to identify them
- How does this slight change in equipment alter our investigation.
- Does the project background require figures.
- Band gap baseline correction.

# Risk Assessment

Monday, 17 January 2022 15:07



Risk\_Assess  
ment\_Op...

# Day 4 in the lab (10th)

Thursday, 10 February 2022 15:17

## Aims:

Configure the python code to read the multimeter.

Figure out size to cut the GaAs.

- We found code for the Keithley multimeter online on PyVISA to talk to the DAAQ card.
- We ran simple scripts using PyVISA to understand how to communicate with the multimeter, with the code at the present moment, the voltage was being produced from the multimeter. Therefore the code needs to be changed such that the voltage is acquired from the multimeter.
- The code is now running fully and a reading can be acquired
  
- We figured that we would like a 2cm x 2cm cut of the GaAs sample.
  - o This will be passed to Jas the technician for cutting.

# Day 5 (11th)

Monday, 14 March 2022

14:30

# Day 6 (14th)

Monday, 14 March 2022 14:30

# Day 7 (15th)

Monday, 14 March 2022 14:30

# Day 8 (21st Feb)

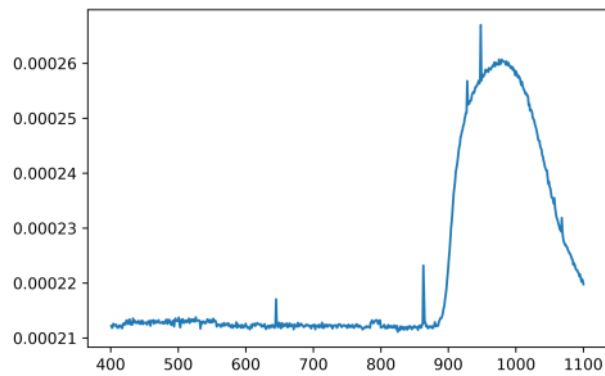
Monday, 21 February 2022 14:31

## Aims:

- Figure out why we are getting a spectrum similar to the expected spectrum without corrections.
  - Figure out the best solution to mount the sample.
- 
- Using the Thorlabs benchtop equipment, we found a suitable mount to house the sample.
    - o This can be seen below.
      - It is important to remember to always handle the sample with gloves to avoid getting fingerprints and dust on it.

We are still unsure why we are getting a spectrum similar to expected sensitivity spectrum without using any correction so we did a crude run with the sample in between the light source and diode. The result shown below is somewhat rewarding.





This is a little bit similar to what we expect. A rise in voltage in between the 800nm to 900nm range. We are still unsure what the spikes in the spectrum are.

### Key takeaways:

Doing a crude run through we can get a plot close to what we expect. Now would be appropriate time to see if this plot is repeatable.



## Day 9 (3rd March)

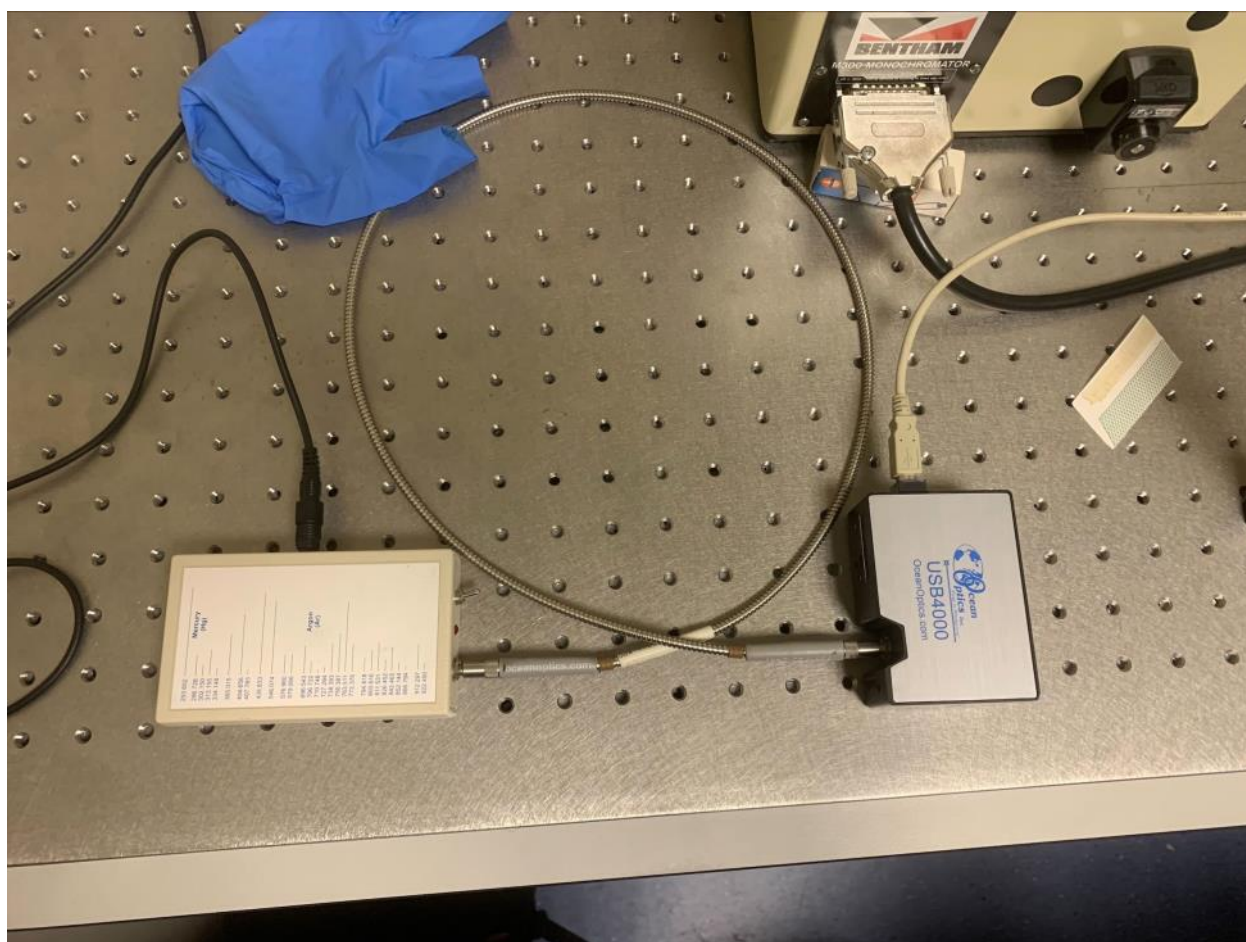
Wednesday, 16 March 2022 15:21

**Disclaimer - Recalibration needed to be redone despite results being achieved as a new ocean optics spectrometer was given to us, so that had to be recalibrated. In addition some changes were made to the slit sizes on both the front and back of the Bentham effecting the width of the wavelengths and also the intensity going through, ergo the recalibration of said equipment needs to be redone**

### Aims:

- Calibrate the Ocean optics.

The Ocean spectrometer needs calibrating as this is still slightly off. We calibrated the Ocean spec using a calibration box.



Calibration  
Oceans

The wavelengths of the calibration box were compared to the wavelengths produced by the Ocean spec in spectra suite. This gave the following data set.



---

## Calibration of the Ocean spectrometer

```
%This section shows the calibration of the ocean spectrometer using  
the  
%calibration source.
```

```
Expected1 = [365.015
```

```
404.656
```

```
407.783
```

```
435.833
```

```
546.074
```

```
576.96
```

```
579.066
```

```
696.543
```

```
706.722
```

```
710.748
```

```
727.294
```

```
738.393
```

```
750.387
```

```
763.511
```

```
772.376
```

```
794.818
```

```
800.616
```

```
811.531
```

```
826.452
```

```
852.144
```

```
866.794
```

```
912.297
```

```
922.45];
```

```
Recorded1 = [367.11
```

```
406.46
```

```
409.60
```

```
438.41
```

```
549.29
```

```
578.51
```

```
580.62
```

```
697.97
```

```
708.17
```

```
716.22
```

```
728.82
```

```
739.84
```

```
751.76
```

```
764.92
```

```
773.91
```

```
796.22
```

```
802.32
```

```
812.81
```

```
827.80
```

```
853.51
```

```
868.20
```

```
913.49
```

```
923.72];
```



---

```
%Remember fluctuation of 0.2nm

Differencel = Recordedl - Expectedl;
%This equation gives the delta between the expected values and the
%recorded values so that we can calculate the standard deviation.

Average = mean(Differencel)
Standard_derivation = std(Differencel)

Standard_error = Standard_derivation/sqrt(length(Differencel))
% This is the associated error on the average

Average =

    1.7920

Standard_derivation =

    0.9246

Standard_error =

    0.1928

Published with MATLAB® R2020b
```

### Key takeaways:

We end up with an average error on the wavelength of 1.792 with an error of +/- 0.2. This means if we get a wavelength value  $x$  on the Oceans spec, the true wavelength will be  $x - 1.792(\pm 0.2)$ .



# Day 10 (14th March)

Monday, 14 March 2022 14:33

## Aims:

- Calibrate the wavelengths of the Bentham using the Ocean spectrometer

We did a preliminary run on the Bentham to see what the difference between the expected and the actual wavelengths is and we found that the difference was not random, but decreased from a difference of 18nm to 12nm in an approximately linear fashion.

When doing a run through of 25 measurements we produced this plot using MATLAB  
The first section of this code is from our calibration of the Ocean spectrometer

---

## Calibration of the Ocean spectrometer

```
%This section shows the calibration of the ocean spectrometer using  
the  
%calibration source.
```

```
Expected1 = [365.015
```

```
404.656
```

```
407.783
```

```
435.833
```

```
546.074
```

```
576.96
```

```
579.066
```

```
696.543
```

```
706.722
```

```
710.748
```

```
727.294
```

```
738.393
```

```
750.387
```

```
763.511
```

```
772.376
```

```
794.818
```

```
800.616
```

```
811.531
```

```
826.452
```

```
852.144
```

```
866.794
```

```
912.297
```

```
922.45];
```

```
Recorded1 = [367.11
```

```
406.46
```

```
409.60
```

```
438.41
```

```
549.29
```

```
578.51
```

```
580.62
```

```
697.97
```

```
708.17
```

```
716.22
```

```
728.82
```

```
739.84
```

```
751.76
```

```
764.92
```

```
773.91
```

```
796.22
```

```
802.32
```

```
812.81
```

```
827.80
```

```
853.51
```

```
868.20
```

```
913.49
```

```
923.72];
```



---

```

%Remember fluctuation of 0.2nm

Differencel = Recordedl - Expectedl;
%This equation gives the delta between the expected values and the
%recorded values so that we can calculate the standard deviation.

Average = mean(Differencel)
Standard_derivation = std(Differencel)

Standard_error = Standard_derivation/sqrt(length(Differencel))
% This is the associated error on the average

Average =

    1.7920

Standard_derivation =

    0.9246

Standard_error =

    0.1928

```

## Calibration of the Bentham monochromator

```

clc

Expected2 = [
400
425
450
475
500
525
550
575
600
625
650
675
700
725
750
775
800
825
850

```

---

```

875
900
925
950
975
1000];

Recorded2 = [416.51
441.12
465.80
490.33
514.93
539.97
564.64
589.53
614.23
639.14
663.84
688.71
713.54
738.33
763.24
788.07
812.81
837.62
862.48
887.02
911.57
936.12
960.96
985.74
1010.74];

Adjusted2 = Recorded2 - Average;

Difference2 = Adjusted2 - Expected2;

standard_deviation2 = std(Difference2);
weights = 1 / standard_deviation2.^2;
weightsplot = weights*ones(length(Difference2),1);

%Using the standard error approach to combine the standard error on
the
%ocean optics offset average and the error of 0.2nm on the read out of
the
%wavelengths on the spectrasuite

error = sqrt(0.2^2 + Standard_error^2 + 0.5^2);
errorplot = error * ones(length(Difference2),1);
clf
hold on
errorbar(Expected2,Difference2,errorplot,'*b')
plot(fittedmodell)
xlabel('Wavelength (nm)')

```

---

---

```

ylabel('Difference in wavelength (nm)')
title('Plot of the difference in wavelength against the wavelength in
spectra')
legend('off')
hold off

Bound = confint(fittedmodel1);
Gradlow = Bound(1,2);
Gradup = Bound(2,2);
Intlow = Bound(1,1);
Intup = Bound(2,1);

Grad_err = (Gradup - Gradlow)/2*1.96
Int_err = (Intup - Intlow)/2*1.96

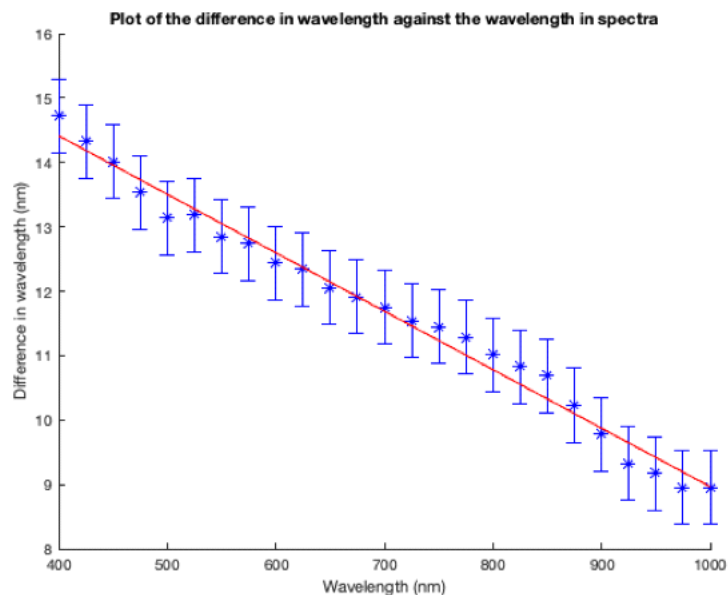
Grad_err =

    9.4712e-04

Int_err =

    0.6846

```



Calibration  
inal

4

It can be seen that difference in wavelength between the actual wavelength of the Bentham and the one inputted using the c file is off by a decreasing amount for each wavelength, hence it is not random. Using the straight line correlation created, we can correct each data point for the estimated difference in wavelength.

This correlation can be described by the equation.  $y = -0.0091 (\pm 0.0009)x + 18.1 (\pm 0.2)$  which was generated in MATLAB using cftool.

### Key takeaways:

It can be seen from the wavelength calibration that we get this negative linear relation between the

expected wavelength and the difference between the expected wavelength and the actual wavelength. Therefore when we enter a wavelength input value into the PC we can attain the real wavelength value.



Calibrationf  
inal

# Day 11 (15th March)

Tuesday, 15 March 2022 12:27

## Meeting with Henini @ 10:30

- Discussed the literature review marks
- Went over mistakes made with plan and literature review
- Discussed the calibration needed with this experiment and reviewed the misconceptions we currently had:
  - o Bulb calibration not needed - only real point of interest was the steep intensity change at certain wavelength
    - Also discussed how the bulb calibration made it worse
  - o Photodiode calibration not needed - for similar reasons
  - o Wavelength calibration is the main error
    - The one in which directly effects the results
    - Ocean optics and Bentham have to be wavelength calibrated

## Aims:

- Establish what need to be calibrated after meeting with Henini
- Continues to write the MATLAB code for the Bentham and ocean optics calibration

## Accomplished:

- The main take away being that the bulb calibration does not need to be accounted for at this time, we do still have said calibration if needed for later
  - The reason for not using it, is it adds complications and has an insignificant effect on the results

# 21st Feb -- 12th March

Monday, 14 March 2022 14:32

# Recalibrating OceanOptics

28 February 2022 14:15

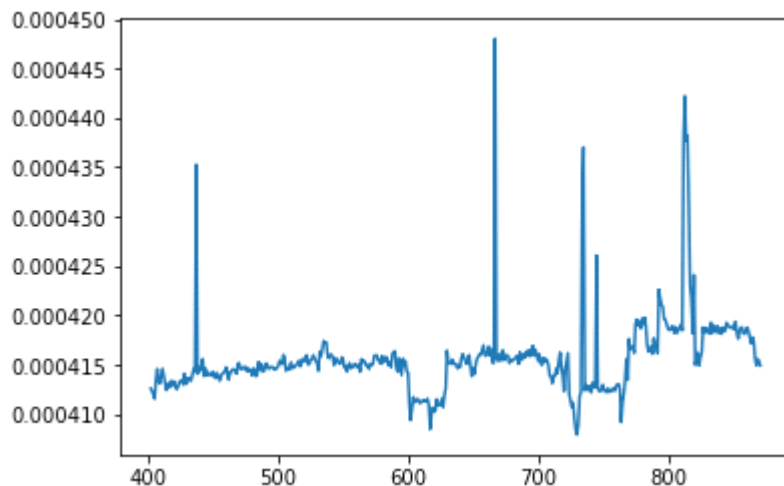
# Day 12

16 March 2022 15:05

## Aims:

- Work out which filters are which as the filters inside the monochromator have been misaligned and are in an incorrect order

## Filter 5



- With ocean spec - essentially no intensity passing through

## Problems:

- At the present moment we are unsure what is going on with the Bentham monochromator and the filter system
  - o The filters are in the wrong positions to the specified manual
  - o We are unsure what filters are in the Bentham
  - o Sometimes it flips to half filters e.g between 1 and 2 but what does that even mean

## What To Do:

- Need to speak with Matt to identify this behaviour associated with the equipment.



# Day 13 (17th March)

Thursday, 17 March 2022 15:27

## Aims:

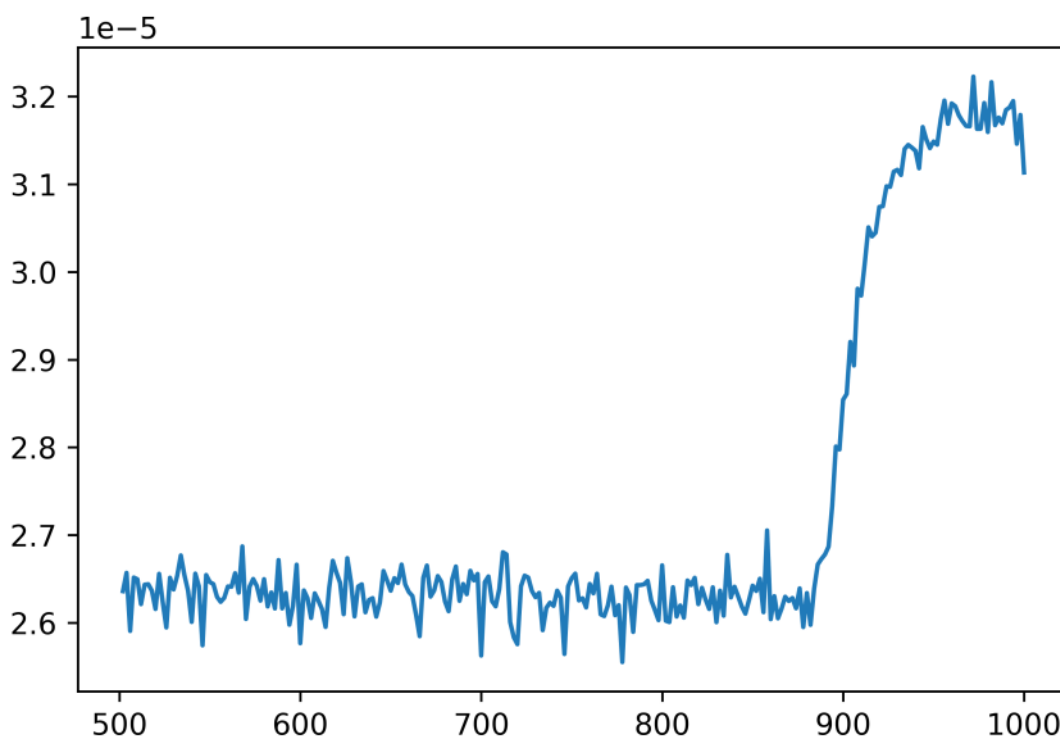
Get Bentham working.

By switching to start the Bentham on filter 3, when it is at visible light. It will automatically rotate to filter 4 at the 700nm mark.

It should also be noted that the background light reflecting off the walls has a significant impact on the voltage output on the diode.

After figuring out that the Bentham is working ok. A new crude run through was carried with 4 readings per 20ms with a step of 2.

This produced the following plot:



## Key Takeaway:

We can now get something similar to what we were getting before we had the ocean optics and filter trouble. This is close to what we expect. It should be noted that we are getting a significant amount of noise.

## Next Steps:

The next steps will be to address this noise as this will likely have an adverse effect of the accuracy and precision of our bandgap estimation.

The first place to look might be the parameters input to the Bentham being too unrefined.

# Calibration of Bentham Monochromator

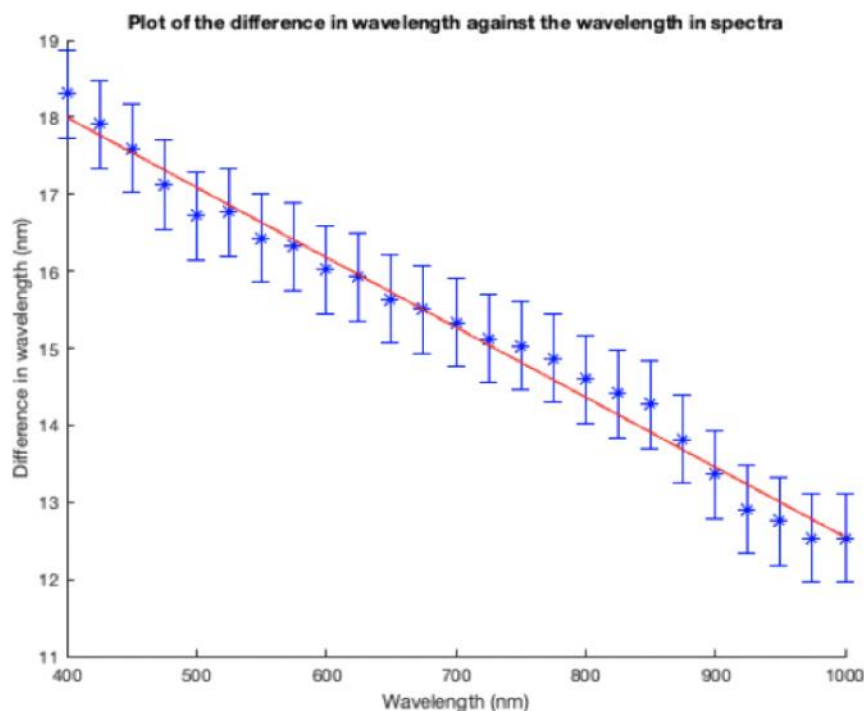
18 March 2022 09:52

- The Bentham monochromator shouldn't be calibrated directly (by calibrating the mechanism itself) but instead should be calibrated via correcting for the systematic error produced instead
- This is due to the calibration process being very cumbersome and technical and therefore the simple solution is to just adjust the systematic error produced

## Challenges to overcome:

*Explain both what's physically happening and also how to tackle these issues*

- The amount the monochromator is off by differs depending on its wavelength in a linear fashion such that there is an overall trend for the error to decrease as the wavelength decreases
- The residuals plot is varying sinusoidally



## Physics & Solutions:

- The sinusoidal variation is probably coming from the mechanism that turns the grating which is almost certainly a worm gear turning a gear wheel that has the grating on it. As the worm gear rotates it may not advance the gear wheel at a uniform rate so you see a sinusoidal variation – search for research articles on calibrating monochromators. As it is a systematic sinusoidal variation it is easy to calibrate out e.g.
  - <https://www.researchgate.net/publication/332747576>  
[Grating monochromator wavelength calibration using an echelle grating wavelength meter](#)
- On your figure the error bars are much larger than the scatter of the points – even before you correct for the sinusoidal variation – this suggests that the error bar is not illustrating a

random uncertainty? It seems as if you have calibrated to better than 1nm which whilst not good enough for atomic physics is sufficient for semiconductor band gap spectroscopy at room temperature.

-

# Day 14 (18th March)

18 March 2022 10:58

## Aims:

- Identify the issues relating to noise in the experiment

## Possible solutions

- Stopping light coming out of the Bentham effecting the results via reflection on the walls
  - Placed black A4 pieces of paper to prevent the reflection
- Changing
  - Response time
    - The rise time of the silicon detector is 14 ns, the time in between each reading is currently 20 ns which should give plenty of time to allow the reading to stabilise. However the time could be increased  $> 25$  ns to see if it has any effect
  - Number of measurements averaged
    - In one reading there can be an associated random error due the precision of the equipment and random noise. This noise leads to natural fluctuations in the results. If, for the same wavelength a number of different readings were averaged over, for example, 20. This would lead to the associated error on the averaged reading to be lower as if has been averaged out. The error in this case would be the error on the mean, which decreases as the number of measurements increases.

# Meeting 4/1

04 January 2022 13:23

- Discussed which photodetector needs to be acquired. Need to contact Matt to purchase the silicon avalanche detector.
- Created GitHub collaboration space.
- Delegated elements of preliminary planning.

# Day 1 in lab

Tuesday, 1 February 2022 15:38

## Notes:

- With a step motor, head only in one direction. Either from short wavelength to long or vice versa.
- Getting two peaks on our Ocean optics spectrometer from monochromator
- When the spectrometer was plugged into the calibrator, we realised there were no longer two peaks, implying that the peaks were coming from the monochromator.
- Need to calibrate ocean spectrometer.
  - o Using 4 milliseconds integration time we got a wavelength spectrum from our Hg/Ar calibration source.
    - We use the 4 milliseconds integration time as it gives us too many photons when the photon number is higher.
  - o We averaged the spectrum over 150 scans to stabilise the fluctuations in the spectrum.
  - o This was then paused to keep the spectrum steady.
  - o The wavelength range 350nm to 1000nm

Expected wavelength (nm)	Predicted wavelength (nm)
365.015	366.90
404.656	406.46
407.783	409.60
435.833	437.58 - cannot be used as the peak is maxed out.
546.074	548.48 - cannot be used as the peak is maxed out.
576.960	578.71
579.066	580.72
696.543	698.17
706.722	708.36
710.748	N/A
727.294	728.82
738.393	739.84
750.387	751.95
763.511	765.11
772.376	773.91
794.818	796.41
800.616	802.69
811.531	812.99

826.452	827.98
842.465	Skipped due to double peak
852.144	853.69
912.297	913.66



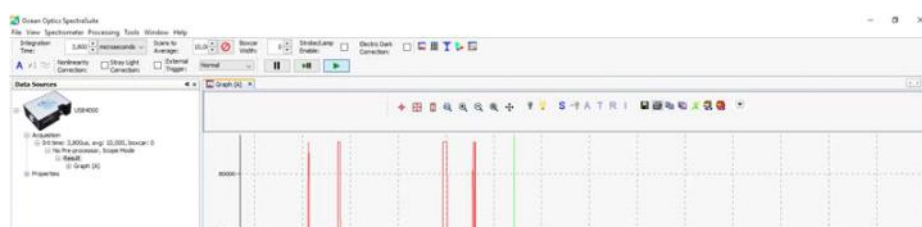
Calibration  
of the oce...

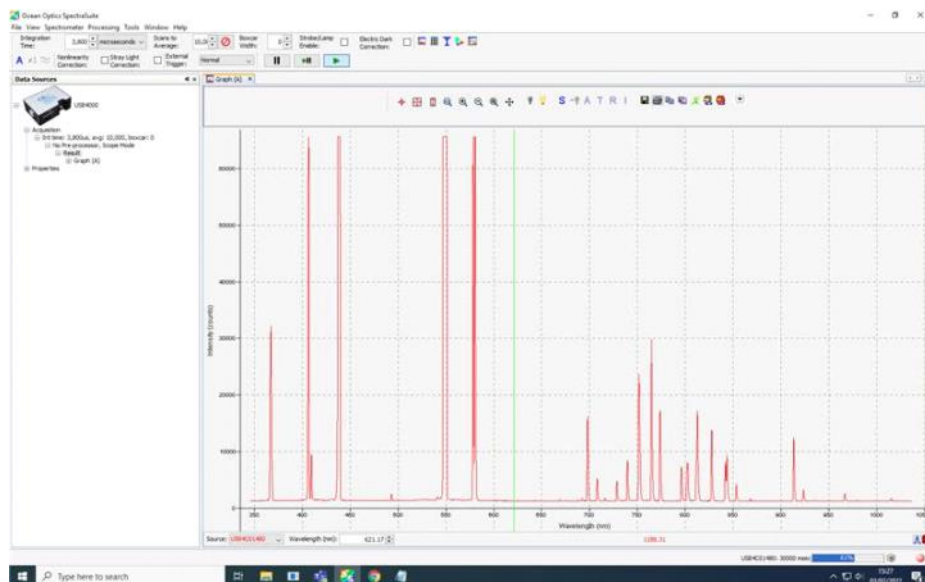


Calibration  
of the oce...

Expected wavelength (nm)	Experimentally calculated wavelengtht ()	Difference (nm)
365.02	366.90	-1.88
404.66	406.46	-1.80
407.78	409.60	-1.82
435.83	437.58 - cannot be used as the peak is maxed out.	N/A
546.07	548.48 - cannot be used as the peak is maxed out.	N/A
576.96	578.71	-1.75
579.07	580.72	-1.65
696.54	698.17	-1.63
706.72	708.36	-1.64
710.75	N/A	N/A
727.29	728.82	-1.53
738.39	739.84	-1.45
750.39	751.95	-1.56
763.51	765.11	-1.60
772.38	773.91	-1.53
794.82	796.41	-1.59
800.62	802.69	-2.07
811.53	812.99	-1.46
826.45	827.98	-1.53
842.47	Skipped due to double peak	N/A
852.14	853.69	-1.55
912.30	913.66	-1.36
Average difference (nm)		-1.63

We calculated an average offset of 1.63 nm from the oceans spectrometer.







# Day 2 in the lab

Thursday, 3 February 2022 15:25

## Aims:

- Calibrate the monochromator
  - Figure out why we get a double peak
- 
- To prevent the ocean spectrometer maxing out we set the aperture of the Bentham to 0.15 mm.
  - The eye of the spectrometer was slightly miss aligned, when we aligned this better

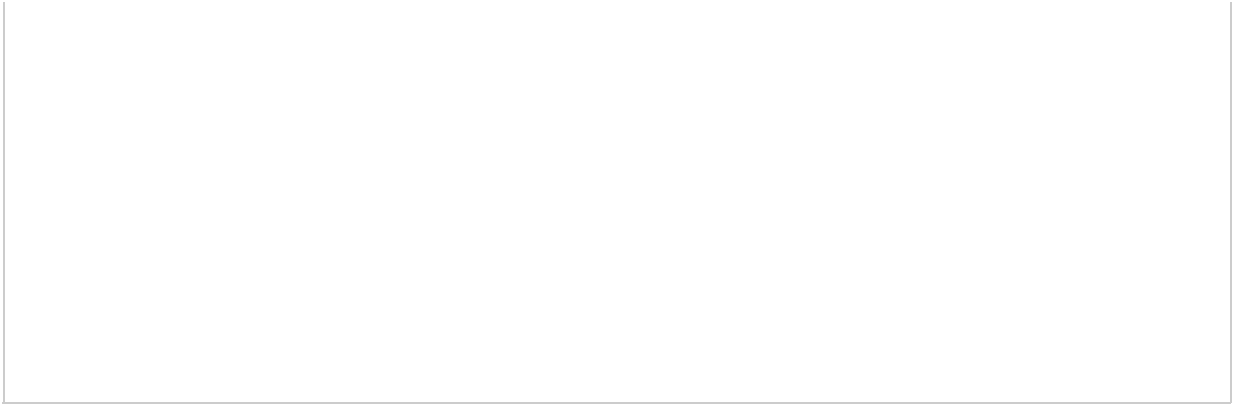


Bentham  
calibration



Bentham  
calibratio...

Target wavelength	Ocean optics wavelenght	Calibrated wavelength
500	510.84	509.21
600	609.87	608.24
700	708.94	707.31
800	807.84	806.21
900	906.86	905.23
1000	1005.85	1004.22



# Getting Started with the Content Library

The Content Library is a place for materials such as readings or worksheets. Think of it as the big filing cabinet for your classroom documents. Only a teacher can put materials into the Content Library. Students can read or copy anything in the Content Library to their own notebooks, but can't modify or delete that content.

## **Here are some ideas for using the Content Library:**

- Ask students to copy pre-made pages from sections like Handouts or Book Reports
- Post important information, such as syllabi, calendars, permission slips, or class rules
- Share course readings and texts
- Store lecture notes
- Capture class whiteboards for future reference

A teacher could organize materials into sections in the Content Library or rely on chronological ordering to keep recent materials near the top for easy discovery by students.



# Welcome to Class Notebook

Your **OneNote Class Notebook** is a digital notebook for the whole class to store text, images, handwritten notes, attachments, links, voice, video, and more.

*Each notebook is organized into three parts:*

1. **Student Notebooks** — A private space shared between the teacher and each individual student. Teachers can access every student notebook, while students can only see their own.
2. **Content Library** — A read-only space where teachers can share handouts with students.
3. **Collaboration Space** — A space where everyone in your class can share, organize, and collaborate.



## How to make the most of Class Notebook in your Class Team:

**Start adding materials or collaborating** in your Class Notebook today. Use the menu to the left to open or add new pages.

**Work in groups.** If you've added channels to your class team, use the **Notes tab** in those channels to continue working together in real time. Each channel connects to its own section in the Collaboration Space.

**Go full-screen.** Launch Class Notebook in full-screen to get more done. Select the double arrow in the upper right of your Microsoft Teams app to expand the window.

**Access more features.** Select **Open in OneNote** to launch Class Notebook in your OneNote app and access more features.

**Learn more.** Check out the [FAQ: Class Notebook in Microsoft Teams](#) page to learn more

# FAQ: Class Notebook in Microsoft Teams

## Where can I get more Class Notebook questions answered?

[OneNote Class Notebook help center](#)

## Questions? Need assistance?

File a support ticket at: <https://aka.ms/EDUSupport>

## Where can I find OneNote and Class Notebook training resources?

A few short interactive courses on the Microsoft Education Center:

- [OneNote Class Notebook: A teacher's all-in-one notebook for students](#)
- [Getting Started with OneNote - Microsoft in Education](#)
- [OneNote: your one-stop resource - Microsoft in Education](#)

## Experiencing permissions issues with your Class Notebook?

[Troubleshoot notebook permissions](#)

## Where do I find the settings to manage my Class Notebook?

Go into your Class Notebook in Teams and click the Class Notebook toolbar, and then click **Manage Notebook**. Teachers can edit sections, copy a notebook link, lock the Collaboration Space, or create a Teacher-only section group here.

To manage Collaboration Space permissions or generate parent and guardian links, open Class Notebook in OneNote and then select **Manage Notebooks**.

## Join the conversation on social media:

Twitter: [@OneNoteEDU](#) and [@msonenote](#)

Facebook: [OneNote](#)