Bangladesh University of Engineering & Technology

Department of Electrical and Electronics Engineering

Lab Report

Experiment Name:

1. Light Absorption and Emission Properties of Materials

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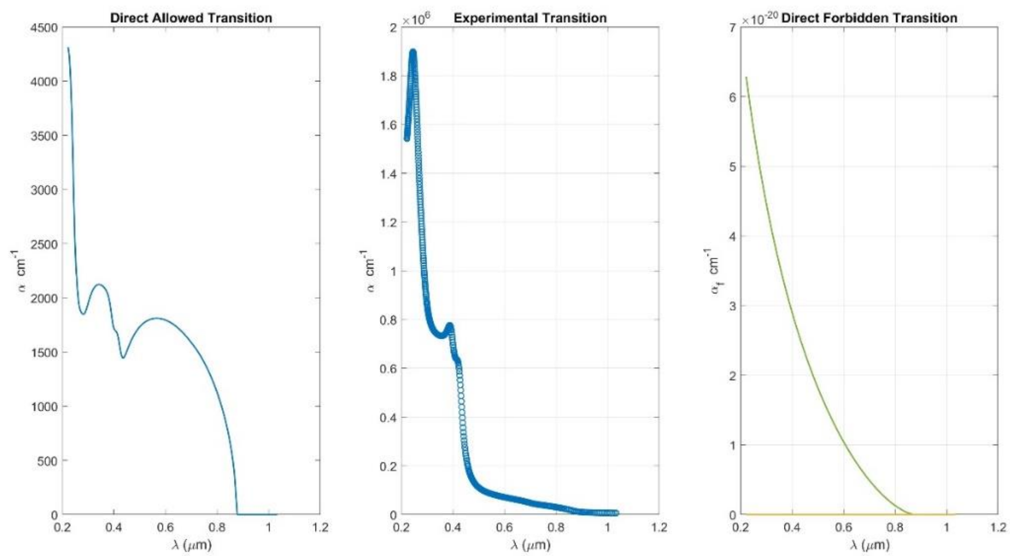
1. Task A

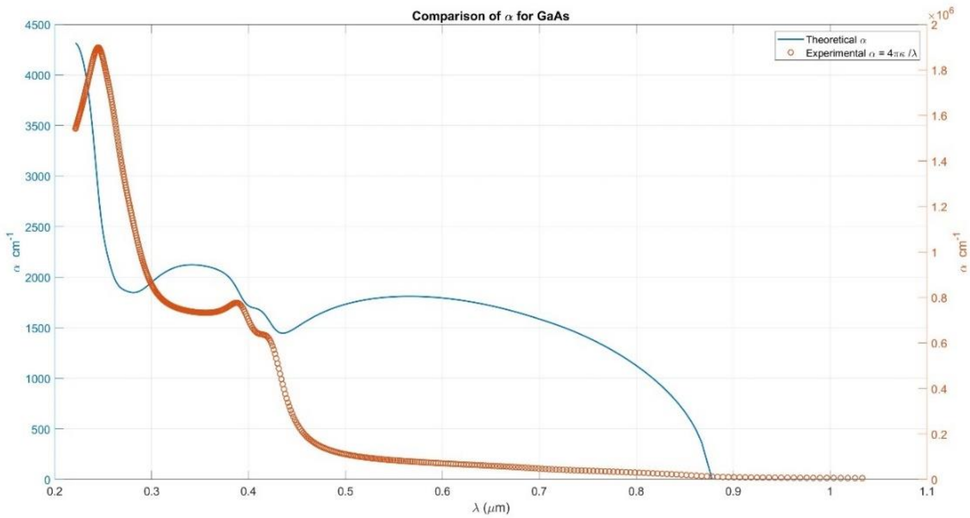
1.1 Lab Task A1

Description:

Theoretically calculate the absorption coefficient of GaAs considering dispersion assuming direct transitions only. Compare your calculated values with the value you obtain from the extinction coefficient of GaAs.

Graphical Output:





Brief Explanation:

If we compare the experimental and theoretical α, we can notice that,

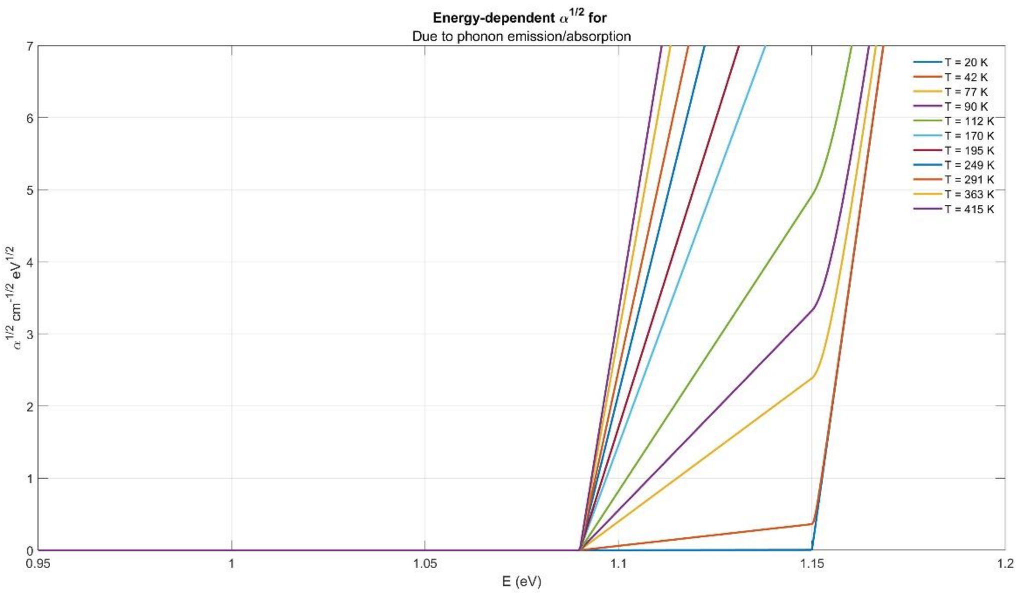
$$\frac{1.9 \times 10^6}{4300} = 441.86$$

So, it is in the order of 2.64.

1.2 Lab Task A2(a & b)

Description

Obtain the proportionality Constant and Plot the Curve



Brief Explanation:

From the graph in the paper [1], temperature 415K has photon energy 1.10 eV for 3.25 cm^-.5 eV^0.5, and without the proportionality constant in our matlab plot, we have got 5.49580e-21 at 1.10eV for 415k.

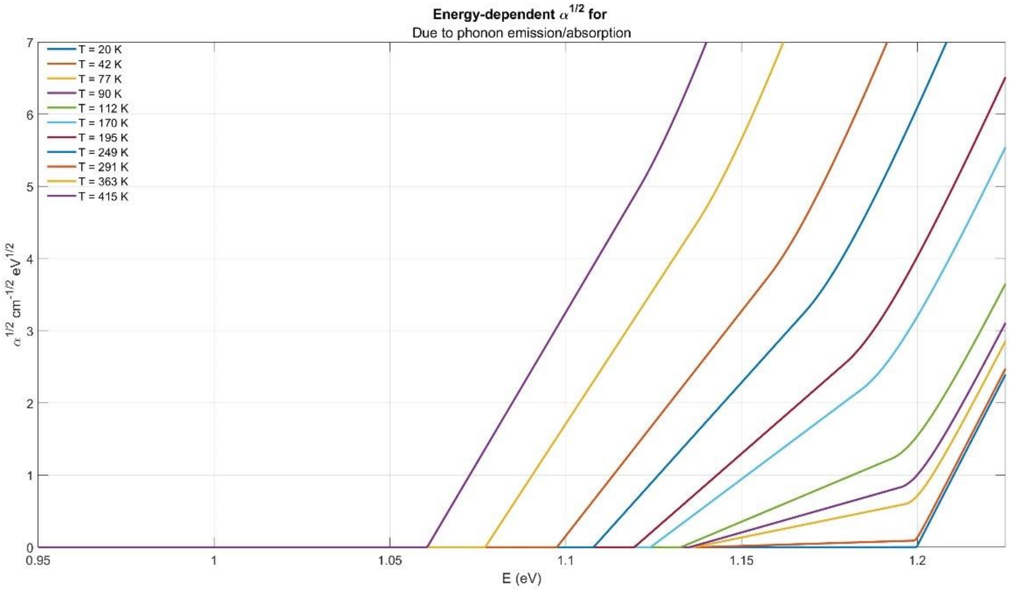
So, the proportionality constant is, $A = \frac{3.25}{0.25 \times 5.49580 \times 10^{-21}} = 5.9135 \times 10^{20}$. Therefore, we can say that the proportionality constant is in the order of 20 that almost matches with our expectation.

1.3 Lab Task A2(c)

Description:

Repeat Task 2(b) considering the temperature dependence of material bandgap. Use Varshni relation to include temperature dependence of material bandgap.

Graphical Output:



Brief Explanation:

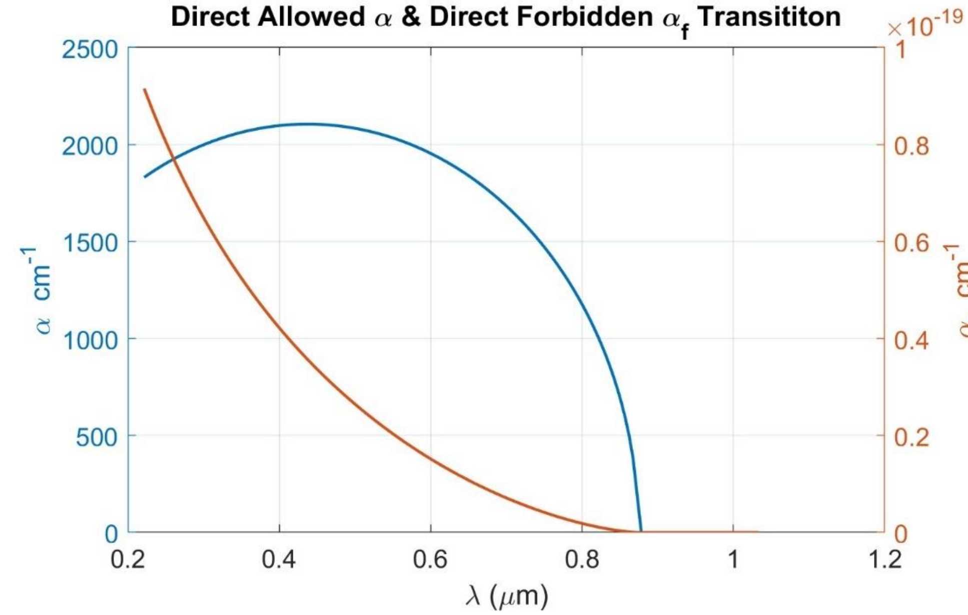
As this considers the temperature dependency, that is why we can see different temperature curve starts from the different position in x-axis.

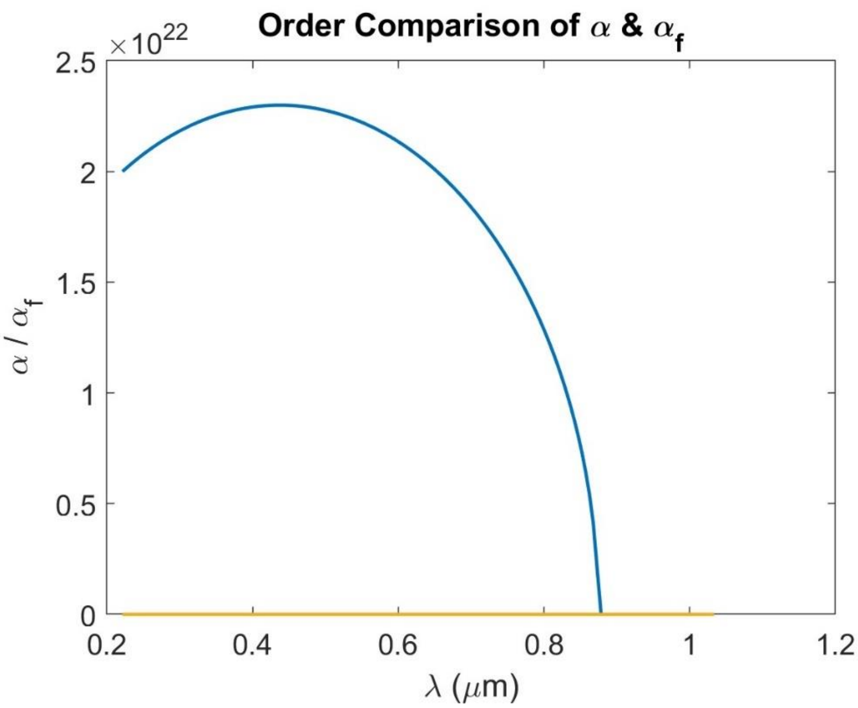
1.4 Report Writing Task A1:

Description:

Without considering material dispersion (i.e., assuming refractive index to be independent of wavelength), calculate and compare the absorption coefficient of a material for allowed direct transition and forbidden direct transition.

Graphical Output:





Brief Explanation:

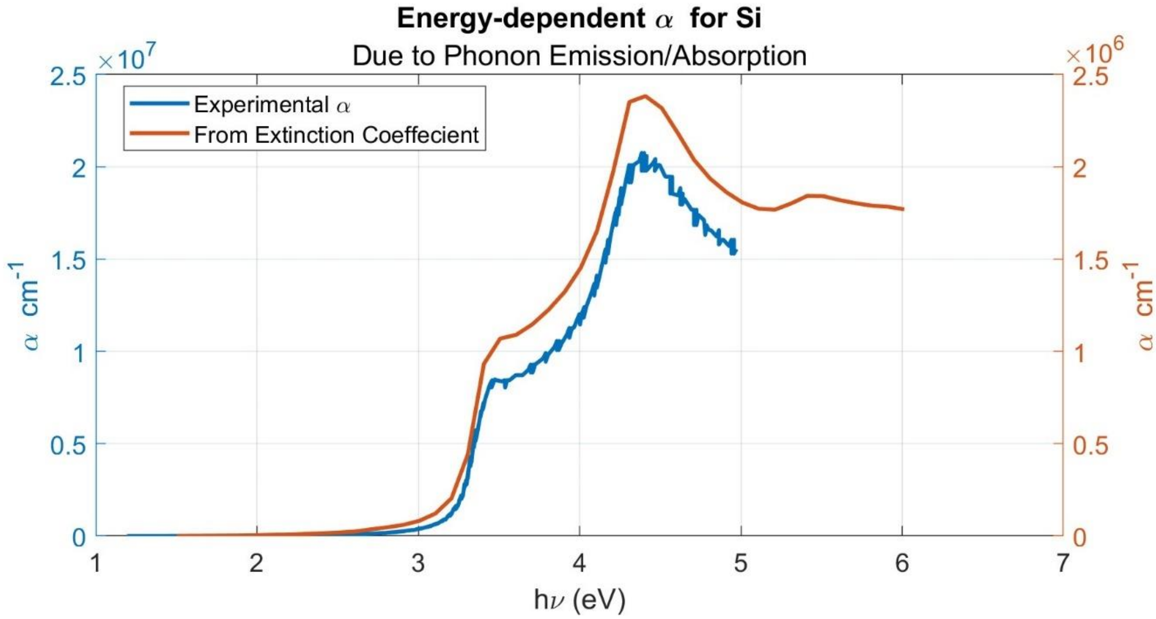
From the above graph, we can notice that the ratio of direct and forbidden transition for the α is in the order of 22. So, we can neglect the values of forbidden transition which is very unlikely to happen.

1.5 Report Writing Task A2:

Description

Collect experimentally reported absorption coefficient values of Silicon, InP and SiO2. Theoretically calculate absorption coefficients for these materials using their extinction coefficients and compare with the experimental results. Also, comment on the possible origins of the differences between theoretical calculations and experimental results.

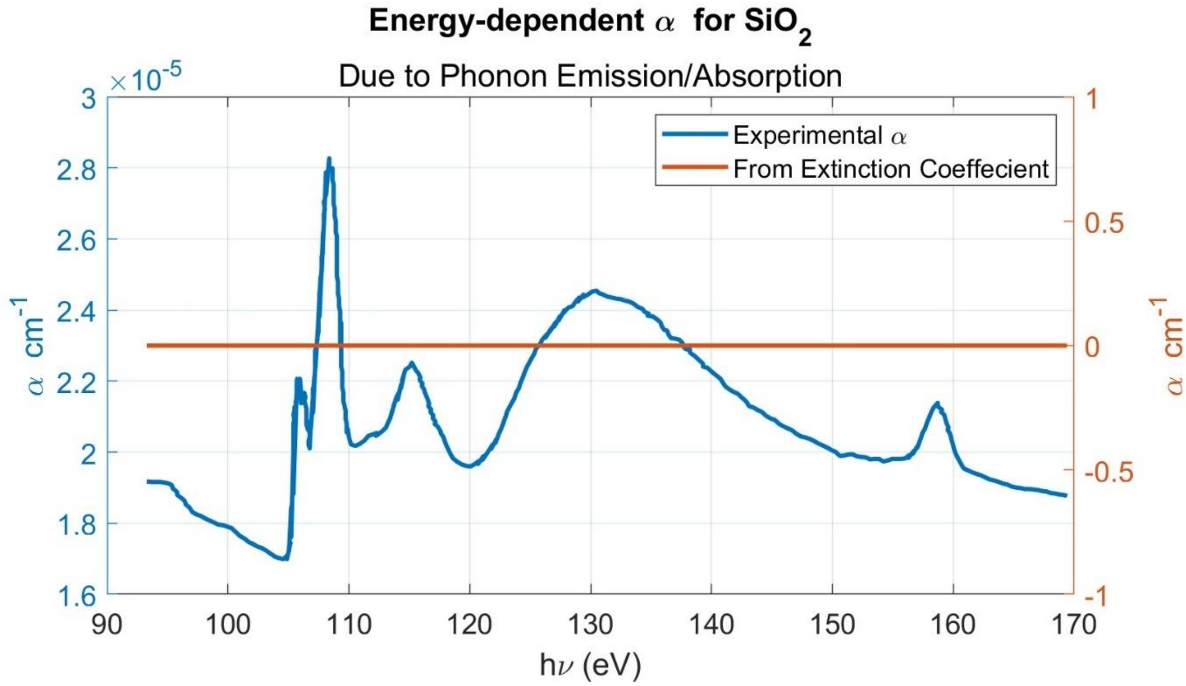
Graphical Output of Si from [Paper [2]]:



Brief Explanation:

The shapes of the curves from experimental and theoretical values are closely aligned, though their absolute values differ. As we don't know the exact procedure of the experiment, there could be some deviation in units or others.

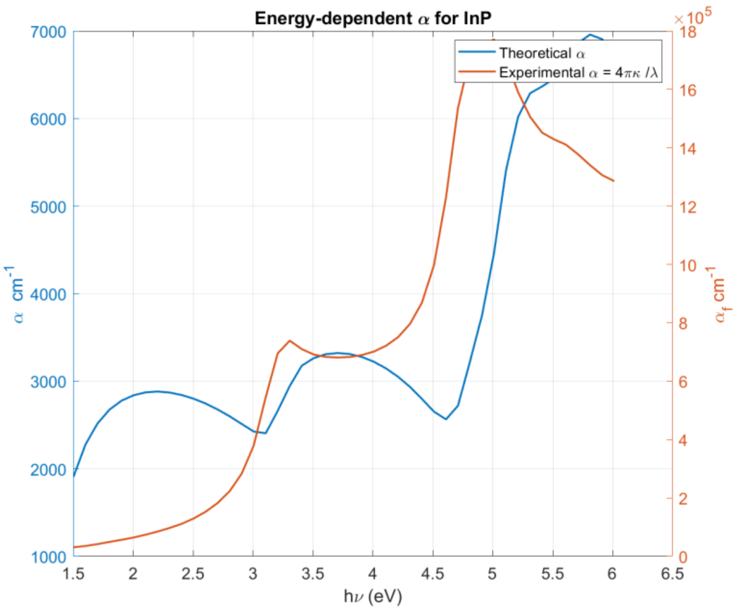
Graphical Output of SiO_2 From Paper [3]:



Brief Explanation:

SiO2 is an insulating material, hence theoretical absorption should be zero. However, due to defects and other non-ideality in experimental setup, we get some but very low absorption.

Graphical Output of InP from [Paper [4]]:



Brief Explanation:

There are discrepancies between the theoretical and experimental graphs at both high and low energies. These could be due to the use of an inaccurate theoretical model for III-V semiconductors or potential errors in the experimental setup.

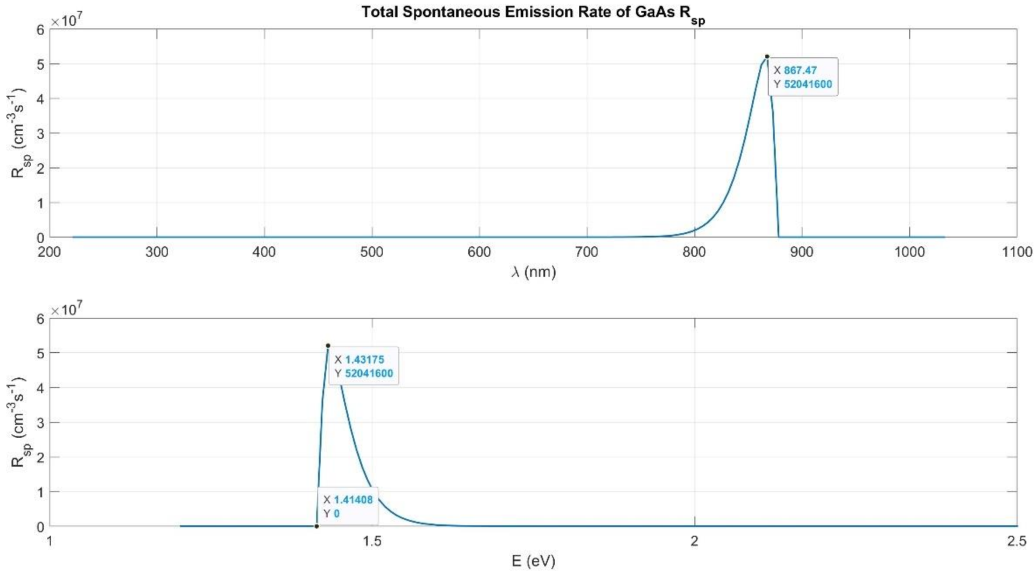
2. Task B

2.1Lab Task B1:

Description:

Numerically calculate the total spontaneous emission rate of GaAs assuming direct transitions only using the absorption coefficient calculated during Laboratory Task 1 of Part A. Plot the spontaneous emission rate of GaAs as a function of photon energy. Also, plot the wavelength dependence of the spontaneous emission rate of GaAs.

Graphical Output:



Brief Explanation:

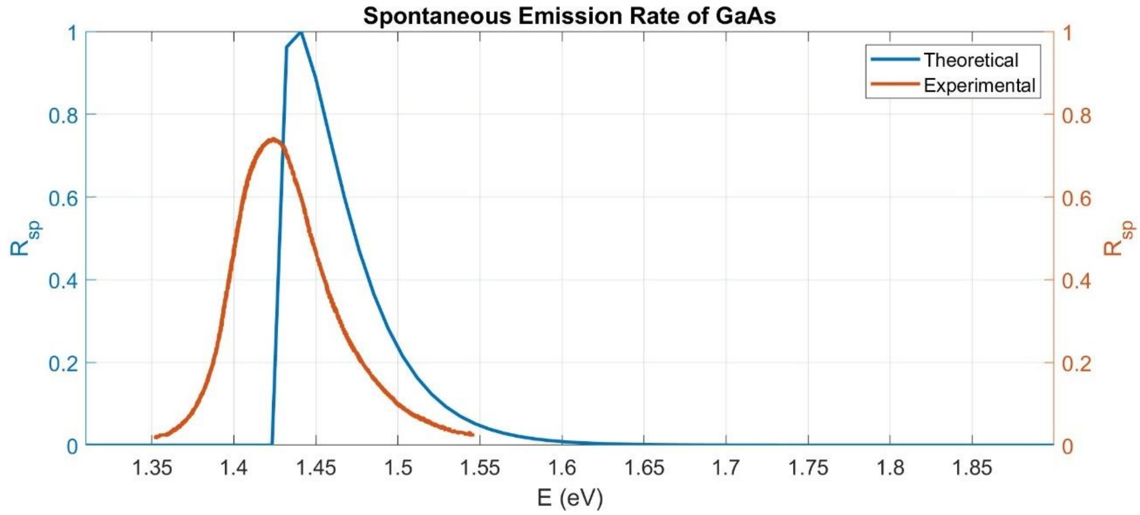
Total spontaneous emission rate of GaAs peaks at E = 1.42eV which is close to the bandgap of the material.

2.2Report Writing Task B1:

Description:

Compare your calculated spectra with the spectra collected from literature.

Graphical Output using Paper [5]:

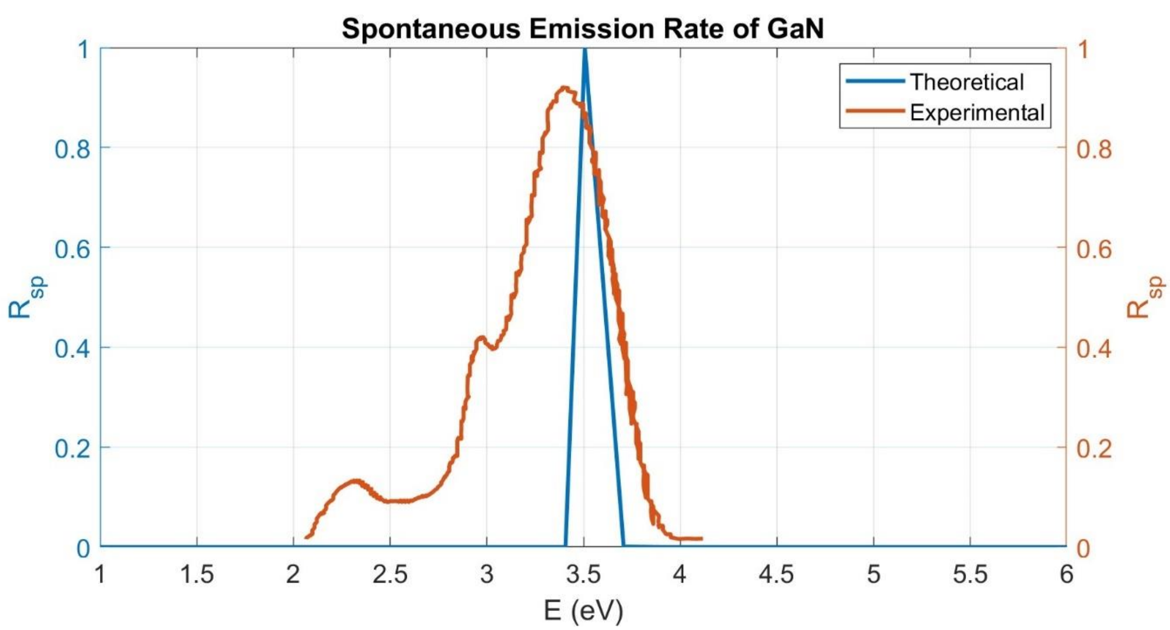


Brief Explanation:

The experimental spectra collected from literature is wide compared to theoretical data. But both graphs peak at the bandgap of GaAs. The reason behind the broad spectrum of experimental data may be because of nonideality of experimental setup and simplified theoretical model.

2.3Report Writing Task B2:

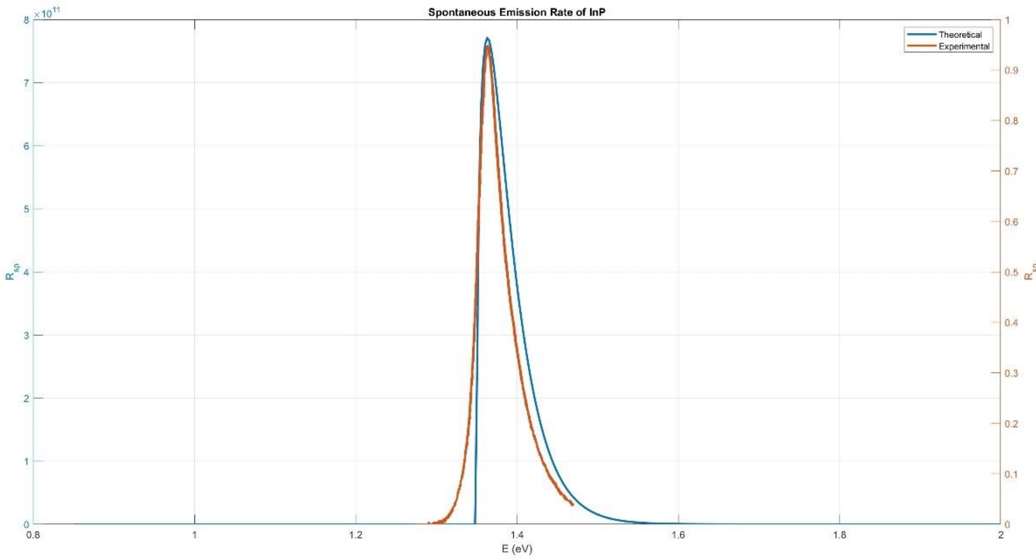
Graphical Output for GaN using Paper [6]:



Brief Explanation for GaN

The experimental spectra obtained from the literature appear broader and more distorted compared to the theoretical data. However, both graphs exhibit a peak near the GaN bandgap, approximately 3.4 eV. The broadening in the experimental spectrum may be attributed to a very simplified theoretical model.

Graphical Output for InP using [Paper [7]]:



Brief Explanation for InP:

The experimental spectra collected from literature almost perfectly matched theoretical data. Moreover, both graphs peak at the bandgap of InP, which is around 1.42eV.

3. Appendix

3.1Code for LabTask A1:

```
clc;
clearvars;
close all;
format long;
set(0,'DefaultAxesFontName', 'Latex');
```

```
set(0,'DefaultAxesFontSize', 13);

%% Loading data
data   = importdata('GaAs2.txt');
lambda = data(:,1);
lambda = lambda.*1e-6; %m
n      = data(:,2);
k      = data(:,3);
m0     = 9.11e-31;
q      = 1.6e-19;
eps0   = 8.854e-12;

%% physical constants
me     = 0.063*m0;
mh     = 0.5*m0;
mr     = me*mh/(me+mh);
h      = 6.624e-34;
hcut   = h/(2*pi);
c      = 3e8;
Eg     = 1.42*q;
fcv    = 23*q;
fcvf   = fcv/1000;
eps    = 12.9*eps0;

nr     = mean(n);

%% Lab Task 1: Compare 'alpha' from 'k' with 'alpha' obtained from formula (using
'n')

E       = h*c./lambda;
% allowed transition
alpha   = q^2*sqrt(m0)./(4*pi*hcut^2*eps*c.*n).*(2*mr/m0)^1.5 .*(fcv./E).*(E-
Eg).^0.5;

% forbidden transition
alphaf  = q^2*sqrt(m0)/(6*pi*hcut^2*eps*c*n) ...
```

```
            .*(2*mr/m0)^2.5 .*(fcvf./E).*(E-Eg).^1.5;  %1/m
%considering dispersion, so used n

figure(1);
% yyaxis left;
subplot(131)
plot(lambda/1e-6, alpha/100,'Linewidth', 1.5);
xlabel ('\lambda (\mum)');
ylabel('\alpha  cm^{-1}');
title('Direct Allowed Transition');
hold on;

% yyaxis right;
subplot(132)
plot(lambda/1e-6, 4*pi*k./lambda/100,'o','Linewidth', 1);
xlabel ('\lambda (\mum)');
ylabel('\alpha  cm^{-1}');
grid on;
title(sprintf("Comparison of \\alpha for %s", 'GaAs'));
title('Experimental Transition');


% figure(2)
subplot(133)
% Direct Forbidden Transition

plot(lambda/1e-6, alphaf/100,'Linewidth', 1.5);
xlabel ('\lambda (\mum)');
ylabel('\alpha_f  cm^{-1}');
title('Direct Forbidden Transition');
subtitle(sprintf(string));
grid on;
```

3.2Code for LabTask A2(a & b):

```
clc;
```

```
clearvars;
close all;

format long;
set(0,'DefaultAxesFontName', 'Latex');
set(0,'DefaultAxesFontSize', 13);

%% physical constants
m0       = 9.11e-31;
q        = 1.6e-19;
eps0     = 8.854e-12;
kB       =  1.38e-23;
h        = 6.624e-34;
hcut     = h/(2*pi);
c        = 3e8;

me       = 0.98*m0;
mh       = 0.16*m0;
mr       = me*mh/(me+mh);

fcv      = 23*q; %constant
fcvf     = fcv/1000;

eps      = 11.9*eps0;
Eg       = 1.12*q;

%% Vashni's law
Eg0      = 1.17; %eV
A        = 7.021e-4;
B        = 1108;

Eg_V     = @(T) (Eg0 - A*T^2/(B + T))*q; %Vashni's law
Ep       = 0.03 * q;     % Typical phonon energy 20-30meV
%% Task 2: Indirect bandgap
Ts       = [20, 42, 77, 90, 112, 170, 195, 249, 291, 363, 415];
% E        = linspace(Eg-0.1*q,Eg+0.2*q,1000);
```

```
E       = linspace(0.95*q,1.3*q,1000);
eV      = 1.6 * 10^-19;

% Direct Allowed transition
figure(3);
for  T = Ts
     EgT  = Eg; %bandgap does not change with temperature
     alpha = (E>EgT-Ep).*(E - EgT + Ep).^2./(exp(Ep./(kB*T)) - 1) ...
            + (E>EgT+Ep).*(E - EgT - Ep).^2./(1 - exp(-Ep./(kB*T)));
     alpha = (4*5.9135e20)^2.*alpha;   % need to make it work

    plot(E/q, sqrt(alpha),'Linewidth', 2,...
        'DisplayName',sprintf('T = %d K',T));

    hold on;
end
xlabel ('E (eV)');
ylabel('\alpha^{1/2} cm^{-1/2} eV^{1/2}');
title(sprintf("Energy-dependent \\alpha^{1/2} for %s",string));
subtitle("Due to phonon emission/absorption");
% xlim([Eg/q-0.1,Eg/q+0.2]);
xlim([0.95,1.3]);
ylim([0, 7]);
grid on;
legend('Box','off');
```

3.3Code for LabTask A2(C):

```
clc;
clearvars;
close all;
```

```
format long;
set(0,'DefaultAxesFontName', 'Latex');
set(0,'DefaultAxesFontSize', 13);



%% physical constants
m0      = 9.11e-31;
q       = 1.6e-19;
eps0    = 8.854e-12;
kB      =  1.38e-23;
h       = 6.624e-34;
hcut    = h/(2*pi);
c       = 3e8;

me      = 0.98*m0;
mh      = 0.16*m0;
mr      = me*mh/(me+mh);

fcv     = 23*q; %constant
fcvf    = fcv/1000;

eps     = 11.9*eps0;
Eg      = 1.12*q;

%% Vashni's law
Eg0     = 1.17; %eV
A       = 7.021e-4;
B       = 1108;

Eg_V    = @(T) (Eg0 - A*T^2/(B + T))*q; %Vashni's law
Ep      = 0.03 * q;     % Typical phonon energy 20-30meV
%% Task 2: Indirect bandgap
Ts      = [20, 42, 77, 90, 112, 170, 195, 249, 291, 363, 415];
% E       = linspace(Eg-0.1*q,Eg+0.2*q,1000);
E       = linspace(0.95*q,1.3*q,1000);
```

```
eV      = 1.6 * 10^-19;

% Direct Allowed transition
figure(3);
for  T = Ts
     EgT   = Eg_V(T); %From Vashni's law
     %EgT  = Eg; %bandgap does not change with temperature
     alpha = (E>EgT-Ep).*(E - EgT + Ep).^2./(exp(Ep./(kB*T)) - 1) ...
            + (E>EgT+Ep).*(E - EgT - Ep).^2./(1 - exp(-Ep./(kB*T)));
     alpha = (5.9135e20)^2.*alpha;   % need to make it work

% from the graph in the paper, 415K has photon energy 1.10 eV for 3.25 cm^-.5 eV^0.5
% plotted sqrt(alpha), got 5.49580e-21 at 1.10eV for 415k
% so 3.25/5.49580e-21 = 5.9135e20 which is the proportionality constant;
    plot(E/q, sqrt(alpha),'Linewidth', 2,...
        'DisplayName',sprintf('T = %d K',T));

    hold on;
end
xlabel ('E (eV)');
ylabel('\alpha^{1/2} cm^{-1/2} eV^{1/2}');
title(sprintf("Energy-dependent \\alpha^{1/2} for %s",string));
subtitle("Due to phonon emission/absorption");
% xlim([Eg/q-0.1,Eg/q+0.2]);
xlim([0.95,1.225]);
ylim([0, 7]);
grid on;
legend('Box','off');
```

3.4Code for Report Writing Task A1:

```
clc;
clearvars;
close all;
```

```
format long;
set(0,'DefaultAxesFontName', 'Latex');
set(0,'DefaultAxesFontSize', 13);

%% Loading data
data   = importdata('GaAs2.txt');
lambda = data(:,1);
lambda = lambda.*1e-6; %m
n      = data(:,2);
k      = data(:,3);
m0     = 9.11e-31;
q      = 1.6e-19;
eps0   = 8.854e-12;

%% physical constants
me     = 0.063*m0;
mh     = 0.5*m0;
mr     = me*mh/(me+mh);
h      = 6.624e-34;
hcut   = h/(2*pi);
c      = 3e8;
Eg     = 1.42*q;
fcv    = 23*q;
fcvf   = fcv/1000;
eps    = 12.9*eps0;

nr     = mean(n);

%% Lab Task 1: Compare 'alpha' from 'k' with 'alpha' obtained from formula (using
'n')

E       = h*c./lambda;
% allowed transition
alpha   = q^2*sqrt(m0)./(4*pi*hcut^2*eps*c.*nr).*(2*mr/m0)^1.5 .*(fcv./E).*(E-
Eg).^0.5;
```

```
% forbidden transition
alphaf  = q^2*sqrt(m0)/(6*pi*hcut^2*eps*c*nr) ...
            .*(2*mr/m0)^2.5 .*(fcvf./E).*(E-Eg).^1.5;  %1/m
%considering without dispersion, so used nr

figure(1);
yyaxis left;
%subplot(121)
plot(lambda/1e-6, alpha/100,'Linewidth', 1.5);
xlabel ('\lambda (\mum)');
ylabel('\alpha  cm^{-1}');
%title('Direct Allowed Transition');
hold on;

% figure(2)
% subplot(122)
% Direct Forbidden Transition
% subplot(121) %related to 73 no line
yyaxis right;
plot(lambda/1e-6, alphaf/100,'Linewidth', 1.5);
xlabel ('\lambda (\mum)');
ylabel('\alpha_f  cm^{-1}');
title('Direct Allowed \alpha & Direct Forbidden \alpha_f Transititon');
subtitle(sprintf(string));
grid on;

figure(2)
plot(lambda/1e-6,((alpha)/(alphaf)),'Linewidth', 1.5);
xlabel ('\lambda (\mum)');
ylabel('\alpha / \alpha_f');
title('Order Comparison of \alpha & \alpha_f');
```

3.5Code for Report Writing TaskA2:

Note: Model code for Silicon Included to Avoid the Redundancy

```
clc;
clearvars;
close all;
format long;
set(0,'DefaultAxesFontName', 'Latex');
set(0,'DefaultAxesFontSize', 13);

data   = importdata('Si.txt');
lambda = data(:,1);
lambda = lambda.*1e-6; %m
n      = data(:,2);
k      = data(:,3);

% physical constants
Eg0     = 1.17; %eV
A       = 7.021e-4;
B       = 1108;
q       = 1.6e-19;
m0      = 9.11e-31;
h       = 6.626e-34;
hcut    = h/(2*pi);
c       = 3e8;
kB      = 1.38e-23;
eps0    = 8.854e-12;
eps     = 11.9*eps0;
me      = 0.98*m0;
mh      = 0.16*m0;
mr      = me*mh/(me+mh);
fcv     = 23*q;
fcvf    = fcv/1000;
```

```
Eg      = 1.12*q;
nr      = mean(n);

data    = importdata('Si-alpha.txt');
E       = data(:,1); % eV
alpha   = data(:,2); % cm^-1

figure(1)
yyaxis left;
plot(E,alpha,'Linewidth', 2)
xlabel ('h\nu (eV)');
ylabel('\alpha  cm^{-1}');
title(sprintf("Energy-dependent \\alpha %s for Si",string));
subtitle("Due to Phonon Emission/Absorption");
grid on
hold on

Energy = h*c./lambda;

yyaxis right;
plot(Energy/q, 4*pi*k./lambda/100, 'Linewidth', 2);
%plot(E,zeros(1,length(E)),'Linewidth', 2)
ylabel('\alpha  cm^{-1}');
hold on
legend('Experimental \alpha', 'From Extinction Coeffecient');
```

3.6Code for LabTask B1:

```
clc;
clearvars;
close all;
format long;
set(0,'DefaultAxesFontName', 'Latex');
set(0,'DefaultAxesFontSize', 13);
```

```matlab
%% Loading data
data   = importdata('GaAs2.txt');
lambda = data(:,1);
lambda = lambda.*1e-6; %m
n      = data(:,2);
k      = data(:,3);
m0     = 9.11e-31;
q      = 1.6e-19;
eps0   = 8.854e-12;


%% physical constants
me     = 0.063*m0;
mh     = 0.5*m0;
mr     = me*mh/(me+mh);
h      = 6.624e-34;
hcut   = h/(2*pi);
c      = 3e8;
Eg     = 1.42*q;
fcv    = 23*q;
fcvf   = fcv/1000;
kB     = 1.38e-23;
eps    = 12.9*eps0;
T      = 300;

%% Numerically calculate the total spontaneous emission rate
E      = h*c./lambda;

% allowed transition
% nr for fixed refractive index
% n for dispersion
alpha = q^2*sqrt(m0)./(4*pi*hcut^2*eps*c.*n) ...
            .*(2*mr/m0)^1.5 .*(fcv./E).*sqrt((E-Eg));
alpha = real(alpha);
P     = alpha .* (c./n);
phi   = 8*pi.*(E/h).^3.*n.^3./c^3   .*  (1./(exp(E/(kB*T)) - 1));
```

```
rsp   = P.*phi;

figure(1);
subplot(211)
plot(lambda/1e-9,real(rsp)/100,'Linewidth', 1.5);
xlabel('\lambda (nm)');
ylabel('R_{sp} (cm^{-3}s^{-1})');
title("Total Spontaneous Emission Rate of GaAs R_{sp}");
grid on;

subplot(212)
plot(E/q,real(rsp)/100,'Linewidth', 1.5)
xlabel('E (eV)');
ylabel('R_{sp} (cm^{-3}s^{-1})');
xlim([1 2.5])
grid on;
```

3.7Code for Report Writing Task B1:

```
clc;
clearvars;
close all;

data     = importdata('GaAs2.txt');
lambda   = data(:,1);
lambda   = lambda.*1e-6; %m
n        = data(:,2);
k        = data(:,3);

% physical constants
q        = 1.6e-19;
m0       = 9.11e-31;
h        = 6.626e-34;
hcut     = h/(2*pi);
```

```
eps0     = 8.854e-12;
c        = 3e8;
kB       = 1.38e-23;
me       = 0.063*m0;
mh       = 0.5*m0;
mr       = me*mh/(me+mh);

fcv      = 23*q;
fcvf     = fcv/1000;

eps      = 12.9*eps0;

Eg       = 1.424*q;                    % 300K
nr       = mean(n);                    % GaAs index Kasap

Eg0      = 1.5326; %eV
A        = 8.872e-4;
B        = 572;

Eg_V     = @(T) (Eg0 - A*T^2/(B + T))*q; %Vashni's law
Ep       = 0.03 * q;     % Typical phonon energy 20-30meV

T = 300;

E        = h*c./lambda;

alpha    = q^2*sqrt(m0)./(4*pi*hcut^2*eps*c.*n) ...
             .*(2*mr/m0)^1.5 .*(fcv./E).*sqrt((E-Eg));
% alpha = real(alpha);
P = alpha .* (c./n);
phi = 8*pi.*(E/h).^3.*n.^3./c^3    .*  (1./(exp(E/(kB*T)) - 1));

rsp = P.*phi;

figure(1);
subplot(211)
```

```
plot(lambda/1e-9,real(rsp),'Linewidth', 1.5);
xlabel('\lambda (nm)');
ylabel('R_{sp}');
title("R_{sp}");
subtitle(sprintf(string));
grid on;

subplot(212)
plot(E/q,real(rsp),'Linewidth', 1.5)
xlabel('E (eV)');
ylabel('R_{sp}');
subtitle(sprintf(string));
grid on;

%% Experimental comparison

data = importdata('Rsp_GaAs.txt');
Energy = data(:,1); % eV
Rsp = data(:,2);

figure(2)
yyaxis left;
plot(E/q,real(rsp)/max(real(rsp)),'Linewidth', 2)
xlabel('E (eV)');
ylabel('R_{sp}'); %m^{-1/3}s^{-1}
subtitle(sprintf(string));
grid on
hold on


yyaxis right;
plot(Energy, Rsp, 'Linewidth', 2);
ylabel('R_{sp}');
ylim([0,1]);
xlim([1.31 1.9])
hold on
```

```
legend('Theoretical', 'Experimental');
title('Spontaneous Emission Rate of GaAs')
```

3.8Code for Report Writing Task B2:

Note: The code of GaN is added to avoid redundant addition. Same code is utilized for the InP too.

```
clc;
clearvars;
close all;

%For Rsp, work with GaN3
data = importdata('GaN3.txt');
lambda = data(:,1);


%for GaN3
lambda = lambda.*1e-9; %m
% lambda = lambda.*1e-6; %m


n = data(:,2);
k = data(:,3);

% physical constants
q       = 1.6e-19;
m0      = 9.11e-31;
h       = 6.626e-34;
hcut    = h/(2*pi);
eps0    = 8.854e-12;
c       = 3e8;
kB      = 1.38e-23;
me      = 0.27*m0;
mh      = 0.8*m0;
```

```
mr      = me*mh/(me+mh);


fcv     = 23*q;
fcvf    = fcv/1000;

eps     = 10.4*eps0;

Eg      = 3.44*q;                         % 300K
nr      = mean(n);                        % GaAs index Kasap

% physical constants

nr      = mean(n);


Eg_V    = @(T) (Eg0 - A*T^2/(B + T))*q; %Vashni's law
Ep      = 0.03 * q;     % Typical phonon energy 20-30meV

T = 300;

E       = h*c./lambda;

alpha   = q^2*sqrt(m0)./(4*pi*hcut^2*eps*c.*n) ...
            .*(2*mr/m0)^1.5 .*(fcv./E).*sqrt((E-Eg));
% alpha = real(alpha);
P = alpha .* (c./n);
phi = 8*pi.*(E/h).^3.*n.^3./c^3   .*  (1./(exp(E/(kB*T)) - 1));

rsp = P.*phi;

figure(1);
subplot(211)
plot(lambda/1e-9,real(rsp),'Linewidth', 1.5);
xlabel('\lambda (nm)');
ylabel('R_{sp}');
```

```
title("R_{sp}");
subtitle(sprintf(string));
grid on;

subplot(212)
plot(E/q,real(rsp),'Linewidth', 1.5)
xlabel('E (eV)');
ylabel('R_{sp}');
subtitle(sprintf(string));
grid on;

%% Experimental comparison

data = importdata('Rsp_GaN.txt');
% Energy = data(:,1); % eV
lamda = data(:,1);
Rsp = data(:,2);
Energy =h*c./lamda ;

figure(2)
yyaxis left;
plot(E/q,real(rsp)/max(real(rsp)),'Linewidth', 2)
xlabel('E (eV)');
ylabel('R_{sp}'); %m^{-1/3}s^{-1}
subtitle(sprintf(string));
grid on
hold on

yyaxis right;
plot(Energy/q, smooth(Rsp), 'Linewidth', 2);
ylabel('R_{sp}');
ylim([0,1]);
xlim([1 6])
hold on
legend('Theoretical', 'Experimental');
title('Spontaneous Emission Rate of GaN')
```

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