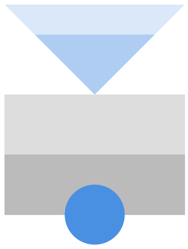
Bangladesh University of Engineering & Technology

Department of Electrical and Electronics Engineering

Lab Report



Experiment No. 3

Name of the Experiment:

Characterization of Light Emitting Diodes (LEDs)

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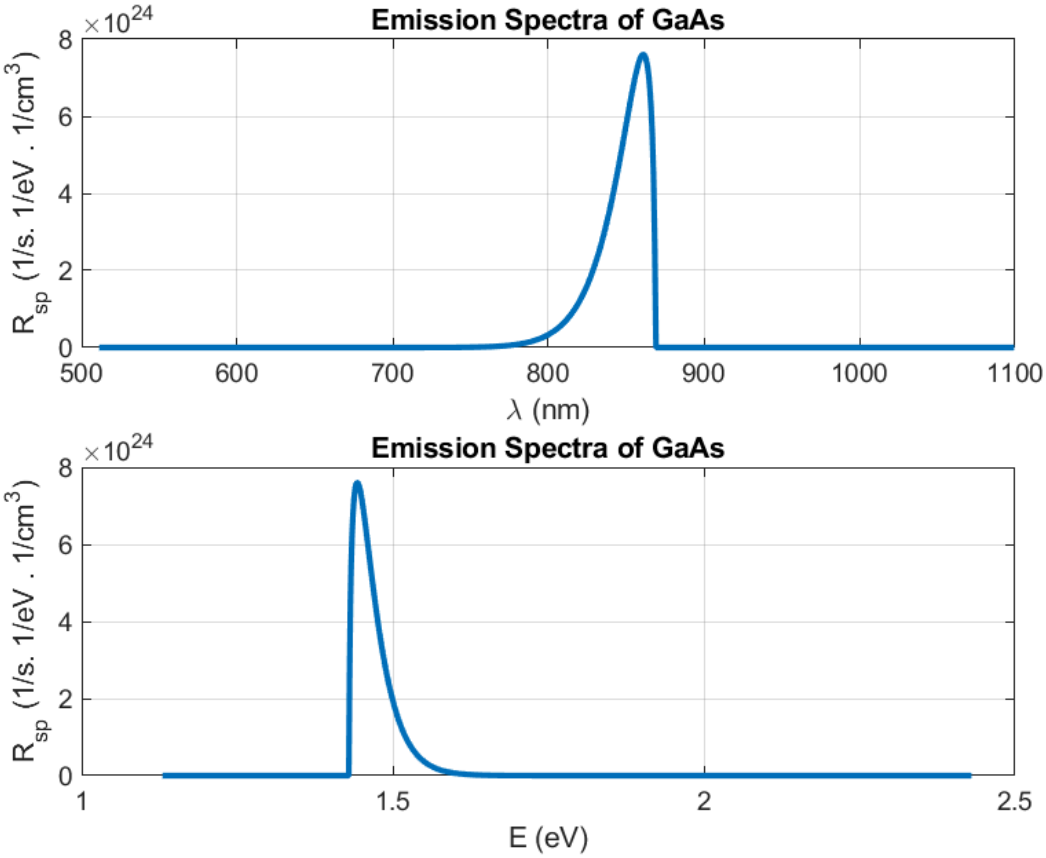
Part A:

Task 1:

Graphical Output:



Calculated Parameters:

Total phonon flux for the LED: 1.302182e+20 1/s

Explanation:

GaAs LED Emission Spectra: The plots show the spontaneous emission rate (Rsp) for GaAs plotted against both wavelength (λ) and energy (E). The key observations are:

1. Peak Emission:

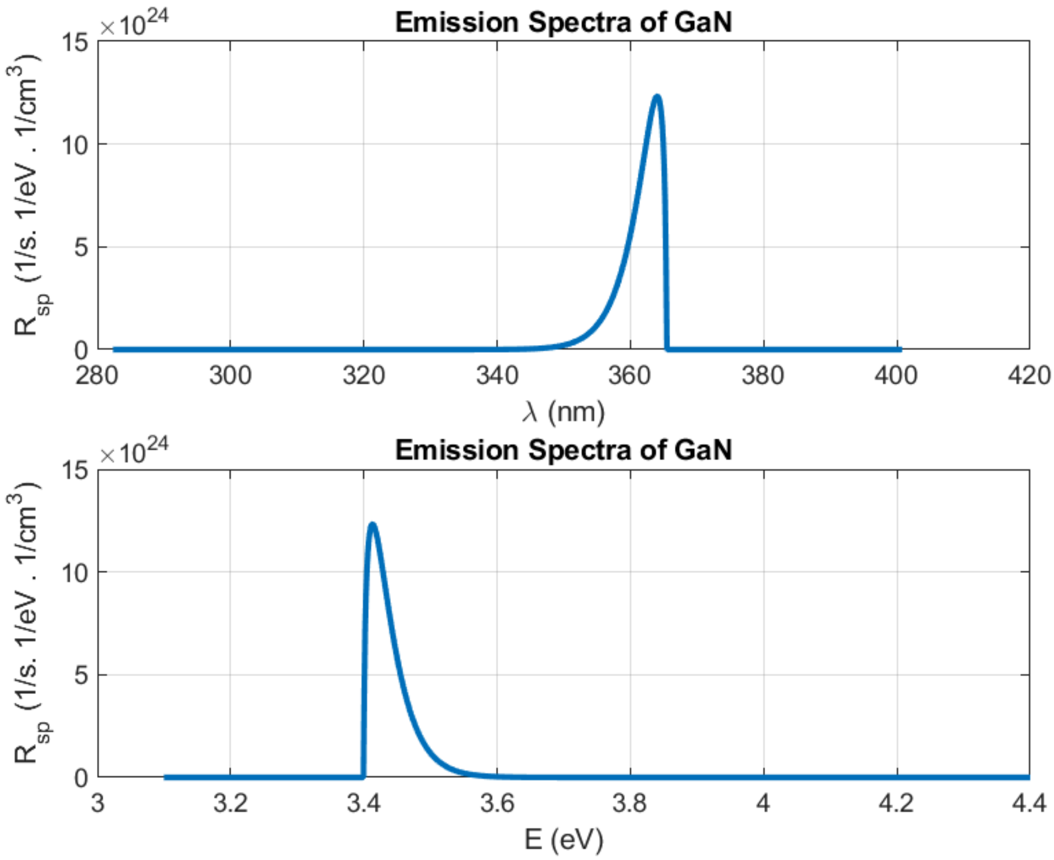
- Wavelength peak occurs at approximately 870 nm
- Energy peak is at around 1.43 eV, which closely matches GaAs's bandgap
- The peak emission rate is about 7.5 × 10^24 cm^-3s^-1eV^-1

2. Theoretical Background:

- The emission spectra follow the relationship: Rsp ∝ n×p×(hν-Eg)^(1/2)×exp(-hν/kT)
- The sharp cutoff at lower wavelengths (higher energies) is due to the exponential term
- The gradual rise is due to the density of states and carrier distributions
- The n+-p junction design (5×10^17 cm^-3 n-type, 10^15 cm^-3 p-type) ensures efficient carrier injection

Task 2:

Graphical Output:



Calculated Parameters:

Total phonon flux for the LED: 2.111738e+20 1/s

Explanation:

GaN LED Emission Spectra: The plots show similar data for GaN, but with notably different characteristics:

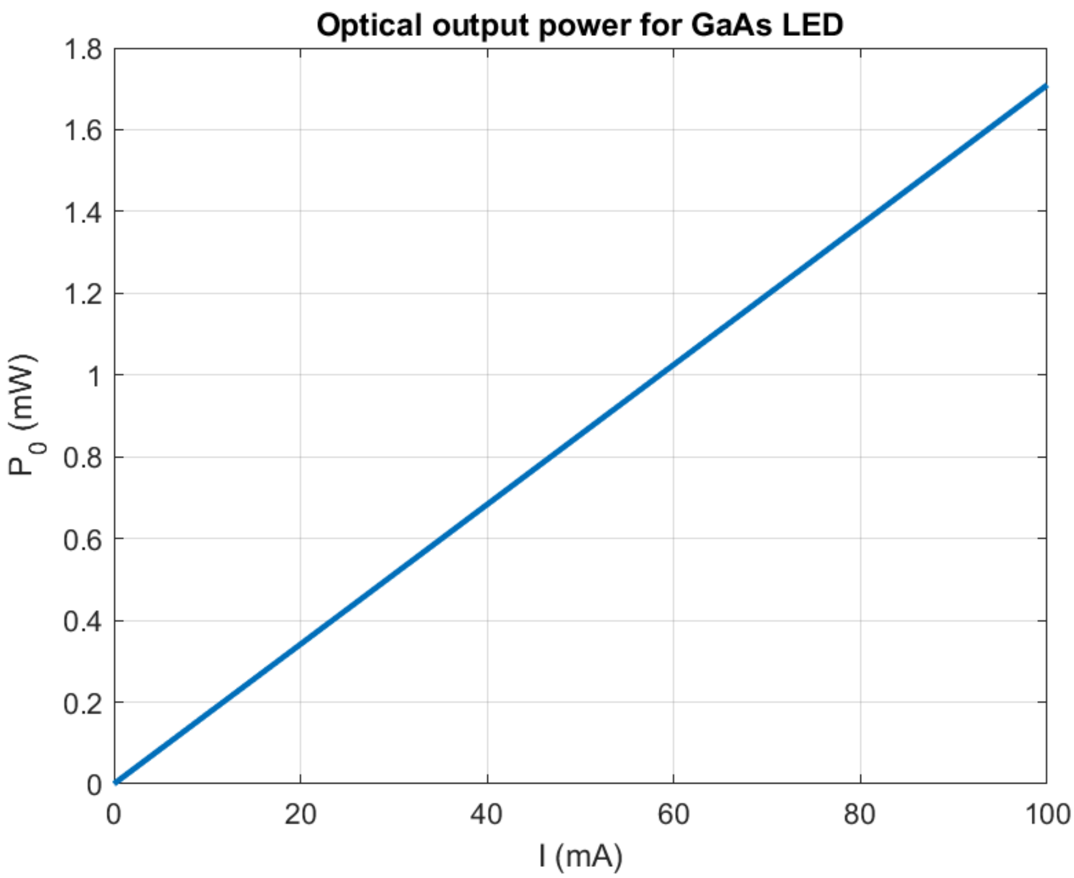
1. Peak Emission:
- Wavelength peak is around 365 nm (UV region)
- Energy peak occurs at approximately 3.4 eV, corresponding to GaN's wider bandgap
- Maximum emission rate reaches about 12.5 × 10^24 cm^-3s^-1eV^-1
2. Key Features:
- The spectrum shows a narrower linewidth compared to GaAs
- Higher peak intensity indicates potentially more efficient recombination
- The higher energy/shorter wavelength emission is characteristic of GaN's wider bandgap
- Similar spectral shape governed by the same physical principles but shifted to higher energy

Both materials show asymmetric spectral shapes typical of semiconductor LEDs, with the position of the peaks determined by their respective bandgap energies. The differences in peak intensities and line widths reflect the active regions' different material properties and carrier concentrations.

Part B

Task 1:

Graphical Output:



Calculated Parameters:

Injection efficiency is 0.99894
Radiative recombination efficiency is 0.95457
Extraction efficiency is 0.01241
luminous efficiency is 0.05072

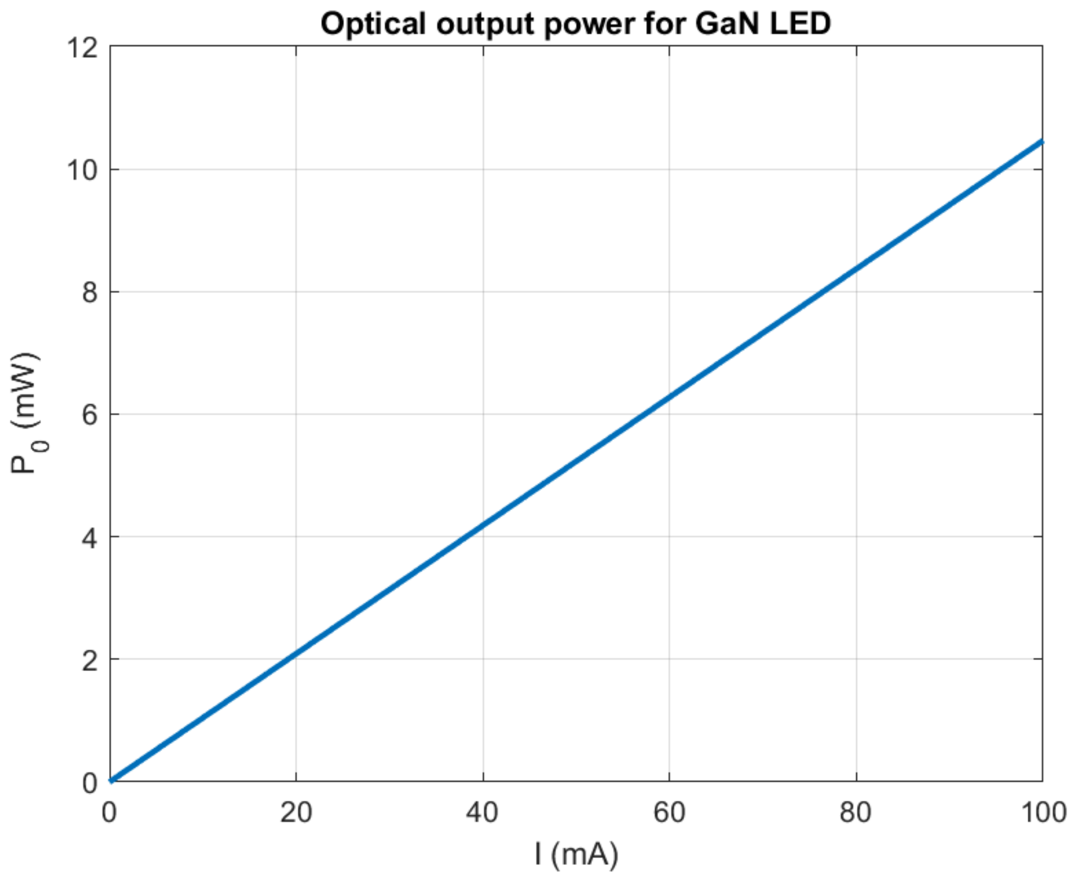
External conversion efficiency is 0.01183

Explanation:

The GaAs n+-p junction LED demonstrates a linear relationship between optical output power and forward current, reaching approximately 1.7 mW at 100 mA. This linearity indicates good carrier injection and recombination characteristics. The calculated injection efficiency of 0.99894 is exceptionally high, attributable to the asymmetric doping (n+ = 5×10^17 cm^-3, p = 10^15 cm^-3) which ensures dominant electron injection into the p-region. The radiative recombination efficiency of 0.95457 suggests that most carriers recombine radiatively rather than through non-radiative processes, indicating good material quality and minimal defect-assisted recombination. However, the extraction efficiency is relatively low at 0.01241, primarily due to GaAs's high refractive index (≈3.6) leading to significant total internal reflection at the semiconductor-air interface. This results in a modest luminous efficiency of 0.05072 and an external conversion efficiency of 0.01183, which represents the overall photon extraction capability of the device.

Task 2:

Graphical Output:



Injection efficiency is 0.99957
Radiative recombination efficiency is 0.97490
Extraction efficiency is 0.03112
luminous efficiency is 0.05101

External conversion efficiency is 0.03032

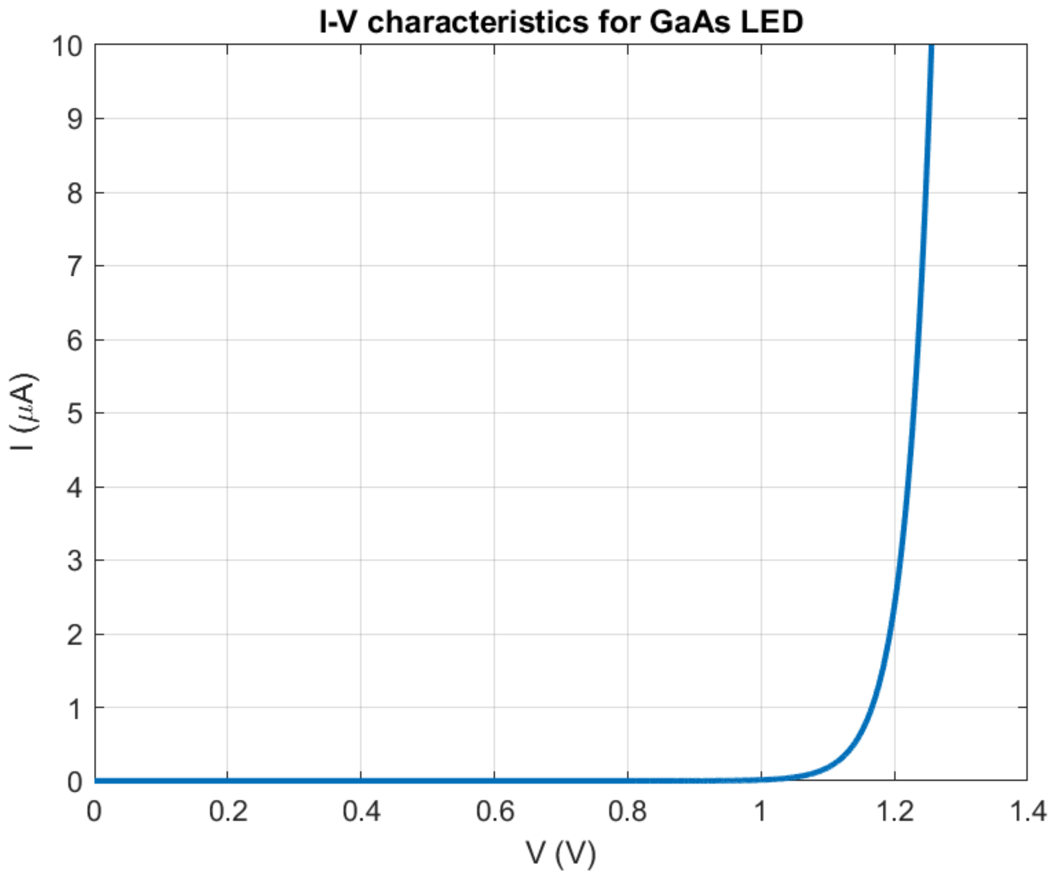
Explanation:

The GaN LED exhibits a steeper linear relationship between optical output power and forward current, achieving approximately 10.5 mW at 100 mA, significantly higher than the GaAs LED. This enhanced performance is reflected in its slightly higher injection efficiency of 0.99957 and radiative recombination efficiency of 0.97490, indicating superior carrier transport and radiative processes. The extraction efficiency of 0.03112, while still low, is better than GaAs due to GaN's lower refractive index (≈2.5) which allows for a larger escape cone at the semiconductor-air interface. The luminous efficiency of 0.05101 and external conversion efficiency of 0.03032 are consequently higher than GaAs. The improved performance of GaN can be attributed to its direct bandgap, strong carrier confinement, and better crystalline quality in modern growth processes. The plots for both LEDs show linear L-I characteristics without saturation within the given current range, indicating good heat dissipation and minimal efficiency droop effects that typically occur at higher current densities.

Part C

Task 1:

Graphical Output:

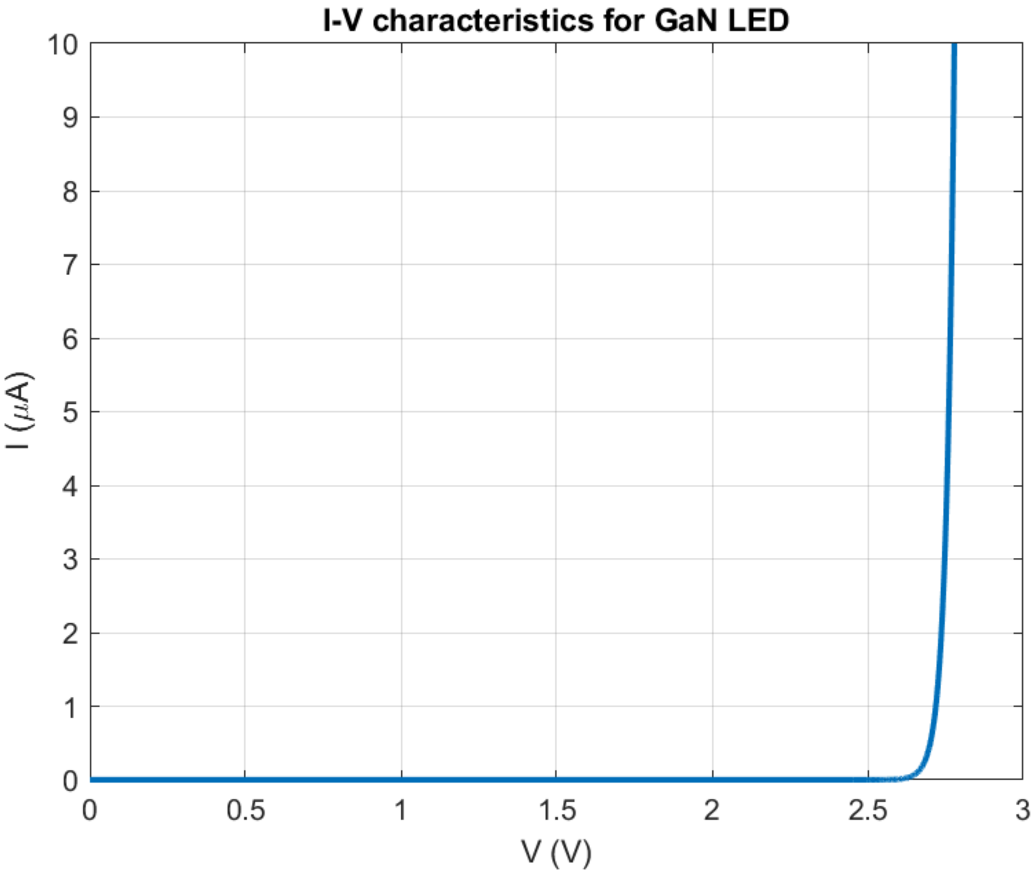


Explanation:

For the GaAs LED, the I-V characteristic shows the typical diode behavior with a turn-on voltage of approximately 1.1V, which corresponds well with GaAs's bandgap energy of about 1.42 eV. The plot demonstrates three distinct regions: a low-current region below turn-on where current is negligible, a sharp turn-on region around 1.1V, and an exponential current increase above turn-on voltage. The asymmetric doping (n+ = 5×1017 cm-3, p = 1015 cm-3) creates a one-sided abrupt junction, which influences the depletion region width and built-in potential. The ideality factor (nf) of 1.5 indicates that both diffusion and recombination currents contribute to the total current flow, typical for real LED devices. The 1 mm^2 cross-sectional area affects the magnitude of the current, with the current reaching approximately 10 μA at 1.3V. The sharp rise in current after turn-on is described by the diode equation $I = Is(\exp(qV/nfkT) - 1)$, where Is is the saturation current.

Task 2:

Graphical Output:



Explanation:

For the GaN LED, the I-V characteristic shows a significantly higher turn-on voltage of about 2.6V, consistent with GaN's wider bandgap of approximately 3.4 eV. The plot exhibits similar regions as the GaAs LED but shifted to higher voltages. The higher doping concentration in the n-region (ND = 1×1018 cm-3) compared to the p-region (NA = 1015 cm-3) ensures efficient electron injection. The ideality factor of 1.0 suggests that the current is dominated by diffusion rather than recombination processes, indicating high-quality material and interfaces. The smaller cross-sectional area of 0.5 mm² compared to the GaAs LED affects the current magnitude, though both reach similar maximum currents of about 10 μA. The steeper turn-on characteristic (more abrupt transition) in GaN compared to GaAs is partly due to the lower ideality factor and higher built-in potential. Both LEDs show negligible reverse leakage current in the shown voltage range, indicating good junction quality and minimal defect-assisted tunneling.

Appendix: Part A

```
clc;
clearvars;
close all;

% Constants in SI unit
h = 6.626e-34;
h_cut = h/(2*pi);
c = 3e8;
k_B = 1.38e-23;
T = 300;
q = 1.6e-19;
mo = 9.1e-31;

%% Choose data
Task_no = 2;   % Task 1: GaAs, Task 2: GaN

switch (Task_no)
    case 1
        material = 'GaAs';
        % Mobility in cm2/Vs
        u_n = 8500;
        u_p = 400;

        % Doping concentrations in (cm-3)
        Na = 1e15;
        Nd = 5e17;

        ni = 1.79e6; % intrinsic carrier concentration (cm-3)

        % effective mass
        me = 0.067*mo;
        mh = 0.5*mo;

        Eg = 1.43*q; % bandgap

    case 2
        material = 'GaN';
        % Mobility in cm2/Vs
        u_n = 1800;
        u_p = 30;

        % Doping concentrations in (cm-3)
        Na = 1e15;
        Nd = 1e18;

        ni = 1.9e-10; % intrinsic carrier concentration (cm-3)

        % effective mass
        me = 0.27*mo;
        mh = 0.8*mo;
```

```
                Eg = 3.4*q;
%bandgap
end

deln = 1e17; % excess
minority carrier
concentration
mr = (me*mh)/(me+mh); %
average effective mass

npo = ni^2/Na;
pno = ni^2/Nd;
Br = 1e-10;

%tau_n means lifetime of
minority electron in
p-region
tau_n =
1/(Br*(Na+npo+deln));
tau_p =
1/(Br*(pno+Nd+deln));

%% Emission Spectra

E =
linspace(Eg-0.3*q,Eg+q,10
00);
lambda = (h*c)./E;
delE = (E-Eg);

%Recombination happens in
p-GaAs region
tau_r = tau_p;
Ef_n =
k_B*T*log((Nd+deln)/ni);
% Ef_n-Ef_i
Ef_p =
k_B*T*log((Na+deln)/ni);
% Ef_i-Ef_p

% Efn_Efp = Ef_n + Ef_p;

R_sp =
((((2*mr)^1.5)/(2*pi^2*(h
_cut^3)*tau_r)) ...
            *exp((Ef_n +
Ef_p-Eg)/(k_B*T)).*(delE.
^0.5).*exp(-delE./(k_B*T)
));

%SI to 1/s. 1/eV . 1/cm3
unit
R_sp_cgs = R_sp*q/100^3;

figure();
subplot(211);
plot(lambda/1e-9,real(R_s
p_cgs), 'LineWidth',2);
xlabel('\lambda (nm)');
ylabel('R_{sp} (1/s. 1/eV
. 1/cm^3)');
title(sprintf('Emission
Spectra of %s',
material));
grid on;

subplot(212);
```

```
plot(E/q,real(R_sp_cgs), 'LineWidth',2);
xlabel('E (eV)');
ylabel('R_{sp} (1/s. 1/eV . 1/cm^3)');
title(sprintf('Emission Spectra of %s', material));
grid on;

% Calculate total spontaneous emission rate
R_total = trapz(E*q, real(R_sp)); % Numerical integration over energy

% Volume in m^3
V = 0.5e-9; % 0.5 mm^3 in m^3

% Calculate photon flux
Phi = R_total / V; % Total photon flux
fprintf('Total phonon flux for the LED: %e 1/s \n',Phi)


% Save the plot as a PNG file
saveas(gcf, 'C:\SPB_Data\EEE460_Jan2024_byakc\Exp3_BYAKC\reportprepare\partA_task2.png');
```

Appendix: Part B

```
clc;
clearvars;
close all;

% Constants in SI unit
h = 6.626e-34;
h_cut = h/(2*pi);
c = 3e8;
k_B = 1.38e-23;
T = 300;
q = 1.6e-19;
mo = 9.1e-31;

%% Choose data
Task_no = 2;  % Task 1: GaAs, Task 2: GaN

switch (Task_no)
```

```
    case 1
                material =
'GaAs';
                % Mobility in
cm2/Vs
        u_n = 8500;
        u_p = 400;

                % Doping
concentrations in (cm-3)
        Na = 1e15;
        Nd = 5e17;

           ni = 1.79e6; %
intrinsic carrier
concentration (cm-3)

        % effective mass
        me = 0.067*mo;
        mh = 0.5*mo;

                % Refractive
index
        nr1 = 3.68; %GaAs

           Eg = 1.43*q; %
bandgap
          lamda0 = 860e-9;
%Peak Wavelength from
Exp1

    case 2
        material = 'GaN';
                % Mobility in
cm2/Vs
        u_n = 1800;
        u_p = 30;

                % Doping
concentrations in (cm-3)
        Na = 1e15;
        Nd = 1e18;

           ni = 1.9e-10; %
intrinsic carrier
concentration (cm-3)

        % effective mass
        me = 0.27*mo;
        mh = 0.8*mo;

                % Refractive
index
        nr1 = 2.55; %GaN

                Eg = 3.4*q;
%bandgap
          lamda0 = 360e-9;
%Peak Wavelength from
Exp1
end

deln = 1e17; % excess
minority carrier
concentration
A = 1*(1/10)^2; %
Cross section Area in cm2
```

```
mr  =  (me*mh)/(me+mh);  % average effective mass


%% Injection efficiency
npo = ni^2/Na;
pno = ni^2/Nd;

% cm2/s
Dn = (k_B*T*u_n)/q;
Dp = (k_B*T*u_p)/q;
Br = 1e-10;

%tau_n means lifetime of minority electron in p-region
tau_n = 1/(Br*(Na+npo+deln));
tau_p = 1/(Br*(pno+Nd+deln));

Ln = (Dn*tau_n)^0.5;
Lp = (Dp*tau_p)^0.5;

Nin = (Dn*npo/Ln)/((Dn*npo/Ln)+(Dp*pno/Lp));  %injection effiiciency
fprintf('Injection efficiency is %0.5f \n',Nin)

%% radiative recombination efficiency
sr = 1e-15;
NT = 1e13; % Trap density (cm-3)
Vth = ((3*k_B*T)/mr)^(.5)*1e2;
tau_nr = (sr*Vth*NT)^-1;

Nr = 1/(1+(tau_n/tau_nr));  % radiative recombination efficiency
fprintf('Radiative recombination efficiency is %0.5f \n',Nr)

%%  Extraction efficiency

%  Refractive index -> nr1-material
nr2 = 1;   %Air

Ne = (1/4)*(nr2/nr1)^2*(1-((nr1-nr2)/(nr1+nr2))^2);
fprintf('Extraction efficiency is %0.5f \n',Ne)

%% luminous efficiency

data = importdata('sensitivity_GaAs.txt');
```

```
lambda = data(5:end,1);
sensitivity =
data(5:end,2);
emission = data(5:end,3);

% figure;
%
plot(lambda,sensitivity)
% xlabel('\lambda (nm)');
% ylabel('Sensitivity');
% title('Photopic
sensitivity');
% grid on;

% Calculating Rsp
E =
(h*c)./(lambda.*1e-9);
delE = (E-Eg);
tau_r =
1/(Br*(Nd+pno+deln));

Ef_n =
k_B*T*log((Nd+deln)/ni);
% Ef_n-Ef_i
Ef_p =
k_B*T*log((Na+deln)/ni);
% Ef_i-Ef_p

Efn_Efp = Ef_n + Ef_p;

R_sp =
((((2*mr)^1.5)/(2*pi^2*(h
_cut^3)*tau_r)) ...
*exp((Efn_Efp-Eg)/(k_B*T)
).*(delE.^0.5).*exp(-delE
./(k_B*T)));

V =
sum(sensitivity.*R_sp);
P = sum(R_sp);
Nl = V/P;
fprintf('luminous
efficiency is %0.5f \n
\n',Nl)

%% Final efficiency
% Excluding NL (as Nl
very low)
N0 = Nin*Nr*Ne;
fprintf('External
conversion efficiency is
%0.5f \n',N0)

%% Output optical power
(L) as a function of
forward current (I)

I = linspace(0,100,100);
%mA
L = N0*I*(h*c/lamda0)/q;
%mW

figure
plot(I,L, 'LineWidth',2);
xlabel('I (mA)');
ylabel('P_0 (mW)');
```

```
title(sprintf('Optical output power for %s LED',material));
grid on;
% Save the plot as a PNG file
saveas(gcf, 'C:\SPB_Data\EEE460_Jan2024_byakc\Exp3_BYAKC\reportprepare\partB_task2.png');
```

Appendix: Part C

```
clc;
clearvars;
close all;

%% Choose data/Task no

Task_no = 2; % Task 1: GaAs, Task 2: GaN

switch (Task_no)
    case 1
            material = 'GaAs';
            % Mobility in cm2/Vs
        u_n = 8500;
        u_p = 400;

            % Doping concentrations in (cm-3)
        Na = 1e15;
        Nd = 5e17;
            ni = 1.79e6; % intrinsic carrier concentration (cm-3)

            A = 1*(1/10)^2; % Cross section Area in cm2
        nf = 1.5;

            lamda0 = 860e-9; %Peak Wavelength from Exp1

    case 2
        material = 'GaN';
            % Mobility in cm2/Vs
        u_n = 1800;
        u_p = 30;
```

```
% Doping concentrations in (cm-3)
Na = 1e15;
Nd = 1e18;

ni = 1.9e-10; % intrinsic carrier concentration (cm-3)

A = 0.5*(1/10)^2; % Cross section Area in cm2
nf = 1;

lamda0 = 360e-9; %Peak Wavelength from Exp1
end
% Peak Wavelength(nm) = 1243/Bandgap(eV)

% Constants in SI unit
h = 6.626e-34;
k_B = 1.38e-23;
T = 300;
q = 1.6e-19;

deln = 1e17; % excess minority carrier concentration

%% Calculation
npo = ni^2/Na;
pno = ni^2/Nd;
% cm2/s
Dn = (k_B*T*u_n)/q;
Dp = (k_B*T*u_p)/q;
Br = 1e-10;

%tau_n means lifetime of minority electron in p-region
tau_n = 1/(Br*(Na+npo+deln));
tau_p = 1/(Br*(pno+Nd+deln));

Ln = (Dn*tau_n)^0.5;
Lp = (Dp*tau_p)^0.5;

V = linspace(0,3,10000);
% Voltage (X-axis)

% Current Density (A/cm2)
Js = q*((Dn*npo/Ln)+(Dp*pno/Lp));

Is = A*Js;
I = Is*exp(((q*V)./(nf*k_B*T))-1);

%% Ploting

plot(V,I/1e-6, "LineWidth",2);
```

```
xlabel('V (V)');
ylabel('I (\muA)');
title(sprintf('I-V characteristics for %s LED',material));

ylim([0 10]);
%                 title('I-V characteristics        of GaAs');
```

```
grid on;

% Save the plot as a PNG file
saveas(gcf, 'C:\SPB_Data\EEE460_Jan2024_byakc\Exp3_BYAKC\reportprepare\partC_task2.png');
```