BANGLADESH UNIVERSITY OF ENGINEERING AND TECHNOLOGY

Department of Electrical and Electronic Engineering

Course No: EEE 460

Course Title: Optoelectronics Laboratory

Project Title:

Characterization of III-V MQW LED for visible wavelength emission

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Objective

Multiple quantum well based (MQW) LED has several advantages over conventional bulk LED in terms of enhanced radiative recombination probability and carrier confinement. In this project, we propose to investigate the carrier dynamics and optical extraction mechanism of a MQW structure using integrated analysis in MATLAB and Lumerical software. Our goals are-

- To investigate the characteristics of GaAs MQW LED devices for visible wavelength emission.
- To analyze the effect of different parameters on the performance of III-Nitride MQW LED devices for visible wavelength emission.
- To analyze spontaneous emission rate & optical extraction mechanism of a MQW structure using MATLAB and FDTD simulation.

Introduction

Light Emitting Diodes (LEDs) have revolutionized the lighting industry due to their energy efficiency, longer lifespan, and environmental sustainability. The development of III-V quantum well (QW) LEDs has played a vital role in the advancement of solid-state lighting technology. These devices have the potential to operate at high efficiency levels and provide high-quality light output in the visible spectrum.

In this project, we aim to characterize the III-V multiple quantum well (MQW) LED for visible wavelength emission. The III-V MQW LED structure is a promising candidate for high-brightness visible light-emitting devices, as it can be engineered to produce specific colors by adjusting the thickness and composition of the semiconductor layers.

The characterization of the III-V MQW LED will involve the measurement and analysis of its electrical and optical properties. The electrical properties will be characterized by performing current-voltage (I-V) characterization. The optical properties will be characterized by analyzing the spectral response and light output power of the LED through FDTD simulations.

Description

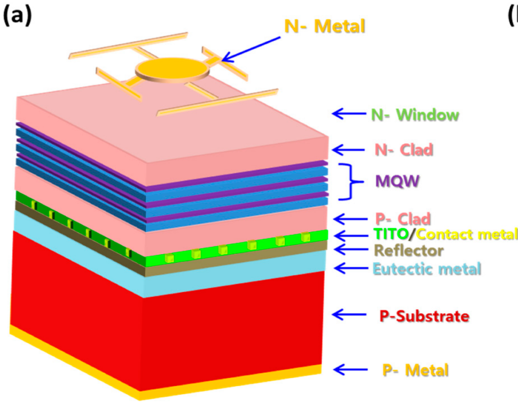
We divide our study in two different decoupled domains -

1. Carrier dynamics and spontaneous emission rate calculation
2. Light extraction and far field pattern from the active region

Carrier dynamics and spontaneous emission rate calculation, involves studying the behavior of carriers within the active region of the LED device, including their recombination and emission processes. By analyzing the carrier dynamics, the efficiency of the device can be figured out. And the spontaneous emission rate can be calculated, which is a critical parameter in determining the device's performance and usability

In the second domain, light extraction and far field pattern from the active region, the behavior of light generated within the active region, including how it interacts with the various layers and interfaces of the device, and how it is ultimately extracted from the device, is studied. Insights into the device's overall performance and efficiency, as well as its suitability for various lighting and display applications, can be gained by analyzing the light extraction and far field pattern. By dividing the study into these two domains, a comprehensive analysis of the LED device can be performed and the device's design and performance can be optimized.

(a)



(b)

Layer	Material	Thickness [nm]
N-metal	NiGeAu	1100 nm
N-Window	$Al_{0.2}Ga_{0.7}As$	3000 nm
N-Clad	n-$Al_{0.3}Ga_{0.6}As$	800 nm
Active (5pairs)	$Al_{0.05}Ga_{0.95}As$ (Barrier)	10 nm
	GaAs (Well)	4 nm
P-Clad	p-$Al_{0.3}Ga_{0.6}As$	800 nm
TITO/ Contact metal	Ti/ITO/AlAu	2nm/ 110nm/ 110nm
Reflector	Ag	300nm
Eutectic metal	Ti/AuIn/Ti	5000 nm
P-substrate	Si	200,000 nm
P-metal	AuBe	600 nm

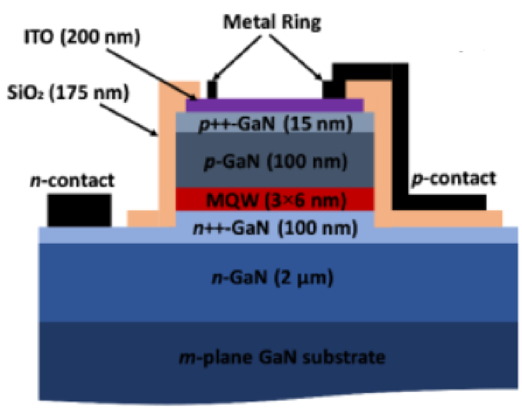


Figure: Representative structure of the MQW LED

Material Selection

Material	Wavelength	Typical number of layers (limited by fabrication process)
GaAs-AlGaAs or AlAs-AlGaAs	600-800 nm	~55
GaN-InGaN or AlGaN-InGaN	300 nm	~12

Theory

Joint density function $N_j(E)$

Selection rules for infinite quantum well: Δn = 0, meaning that transition between conduction and valence subband can only occur when the change in subband quantum number is zero.
The joint density of states of 2D quantum well is

$$N_J(E) \ = \ \frac{m_r}{\pi\hbar^2}.\frac{1}{d}.\sum_i u(E - E_g - E_c^{\ i} - E_V^{\ i}) \ \ eV^{-1} cm^{-3}$$

Where,
m_r is the reduced electron mass,
E^i_C and E^i_V are the i'th subbands for conduction and valence bands.

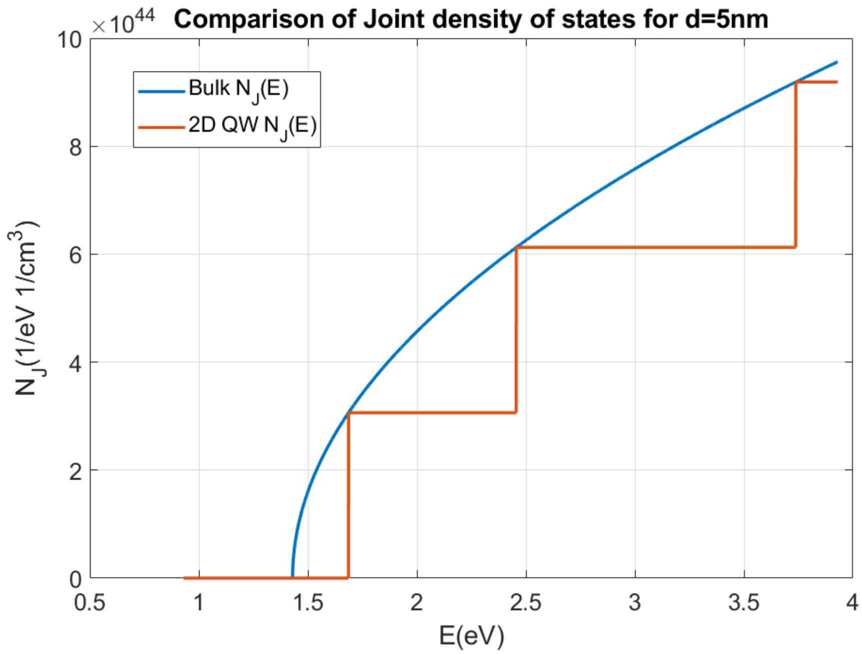


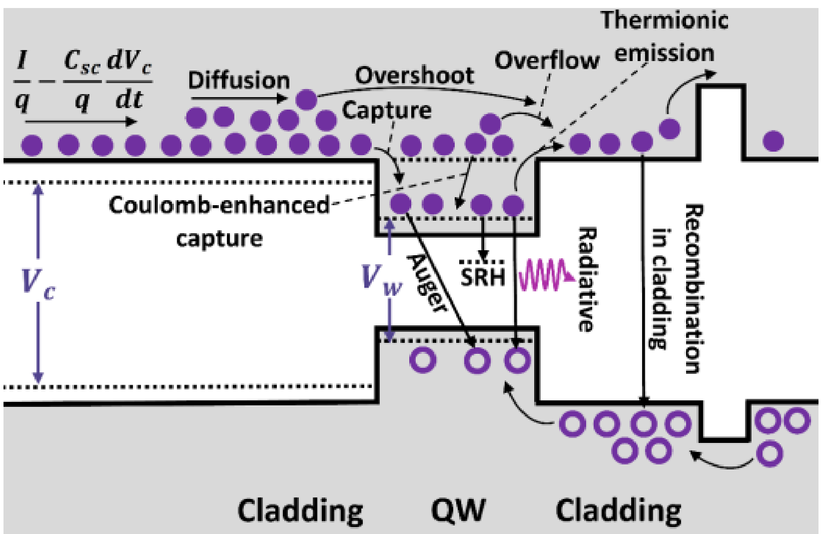
Figure: Comparison of Joint Density of States for a fixed well width

The joint density of states (JDOS) is an important quantity that characterizes the electronic and optical properties of the device. In the above plot, we compared JDOS of 2D QW LED with bulk GaAs LED. The JDOS in MQW GaAs LEDs and bulk GaAs LEDs are different due to their different structures and electronic properties.
In bulk GaAs LEDs, the JDOS is continuous and exhibits a characteristic peak at the bandgap energy. This peak corresponds to the electronic states available for recombination and light emission. The JDOS in bulk GaAs LEDs also depends on doping density and temperature.
In contrast, the JDOS in MQW GaAs LEDs consists of a series of discrete peaks, which correspond to the confined electronic states in the quantum wells. The peak energies and intensities depend on the quantum well geometry, the barrier height and width, and the doping

density. The MQW structure also enhances the radiative recombination rate by confining the carriers to a smaller volume, leading to higher efficiency.
The JDOS in MQW GaAs LEDs can be modulated by changing the number of quantum wells or the barrier thickness, which affects the electronic states available for recombination. This allows for greater control over the emission wavelength and spectral characteristics. Here, we kept the well width fixed.

Carrier dynamics

N_W and N_C are the total carrier number and Vw and Vc are the quasi fermi level separation in the QW and cladding layers, respectively. I is current injected into the cladding layers. Our goal is to calculate the carrier density, n_w and recombination lifetime τ_{rec} in terms of injected current density.



The rate equations governing carrier mechanisms in the QW and cladding layers are as follows

$$\frac{dN_w}{dt} = \frac{N_C}{\tau_C} - \frac{N_W}{\tau_{rec}} - \frac{N_W}{\tau_{esc}}$$

$$\frac{dN_C}{dt} = \frac{I}{q} - \frac{N_C}{\tau_C} + \frac{N_W}{\tau_{esc}} - \frac{N_C}{\tau_{rec,clad}}$$

Here, τ_{rec} and $\tau_{rec,clad}$ are the recombination lifetimes inside the quantum well and cladding region. τ_{esc} is loss/overflow lifetime, τ_C is the transport delay from cladding to the QW region.

At steady state condition,

$$N_w[\frac{\tau_C.\tau_{esc}}{(\tau_{rec} \,||\, \tau_{esc}).(\tau_C||\tau_{rec,clad})} - 1] = \frac{\tau_{esc}}{q} I$$

Assuming $\tau_{rec,clad}$ is smaller than all the other lifetimes,

$$N_w = \frac{\tau_{rec}}{q} I$$

Now, in terms of carrier density n_w in the quantum well, recombination lifetime τ_{rec} can be written as

$$\tau_{rec} = \frac{1}{B_r(n_0+p_0+\delta n)} \sim \frac{1}{B_r n_w}$$

Now, writing $N_w = n_w.A.d$ and $I = J.A$, final expression for recombination lifetime τ_{rec} and carrier density n_w becomes in terms of current density

$$\tau_{rec} = (\frac{B_r}{dq})^{-1/2} J^{-1/2}$$

$$n_w = (\frac{1}{B_r qd})^{1/2} J^{1/2}$$

Finally, probability of radiative recombination/emission P_{em} is given by

$$P_{em} = \frac{1}{\tau_{rec}}$$

Carrier density vale n_w will be used for calculating fermi levels inside the quantum well

$$E_{fn} = k_B T\, ln(\frac{n_w}{n_i})$$

Spontaneous emission rate calculation

Contrary to the bulk 3D LED, MQW based LED works on a different mechanism using subband transition of 2D electron gas inside the quantum wells. With appropriate joint density function $N_j(E)$, emission transition probability P_{em} and selection rule for transition for the MQW structure, we will derive the expression of $r_{sp}(E)$ for 2D electron gas in the QW. We will also incorporate a simple rate equation model to describe the carrier population inside the subband, which will give further insights into high-speed operation of the MQW LED. Additionally, we will investigate how temperature, quantum well width, and number affect the spectrum response and give rise to tuanale nature of the LED.

Spontaneous Emission Rate (R_{sp}) Spectra

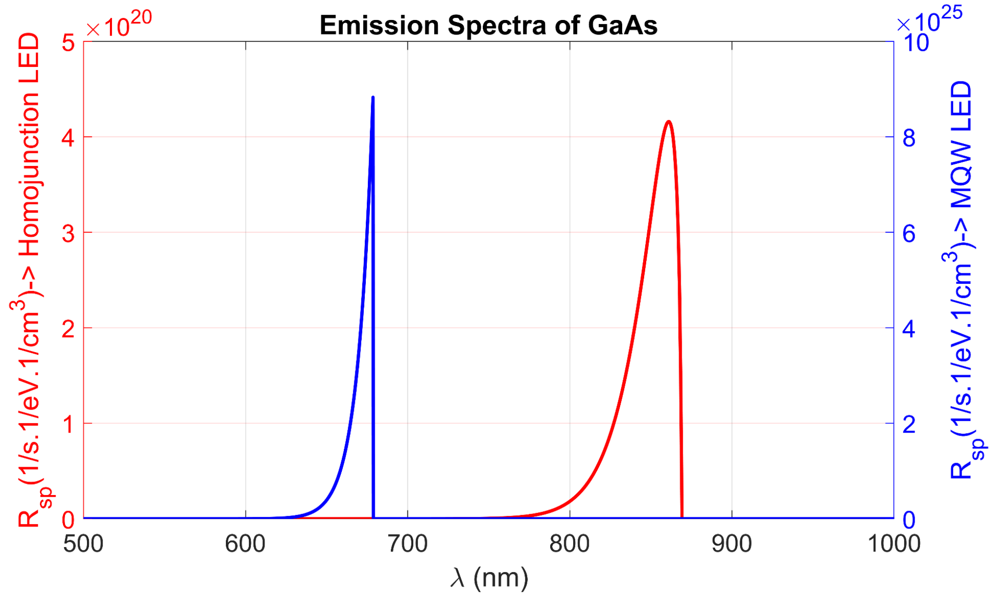


Figure: comparison between emission spectra of GaAs Homojunction and MQW LED

In homojunction GaAs LEDs, the emission spectrum is broad and typically consists of a single peak corresponding to the bandgap energy of the material. This peak is broadened by temperature and other factors, such as impurities and defects. The emission wavelength of homojunction GaAs LEDs is not easily tunable, and the spectral characteristics are relatively insensitive to doping density and carrier injection rate.

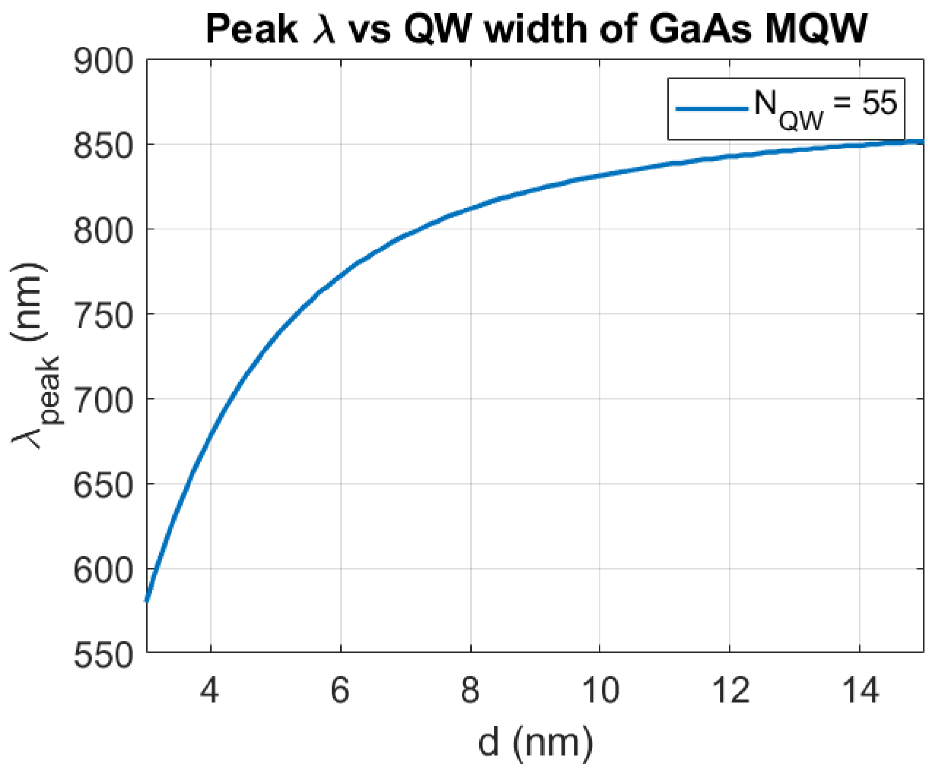
In contrast, the emission spectrum of GaAs MQW LEDs consists of sharp peaks corresponding to the electronic transitions between the confined energy levels of the quantum wells. The MQW structure allows for efficient carrier injection and radiative recombination, as evident from the graph, leading to higher efficiency and brightness compared to homojunction GaAs LEDs. The MQW structure also provides a wider range of emission wavelengths and spectral characteristics than homojunction GaAs LEDs, making them suitable for a broader range of applications.

Study of Optical Extraction

To study optical extraction, we will use the $r_{sp}(E)$ data calculated in the previous section to characterize external quantum efficiency, luminosity, and far-field emission patterns. Using surface emitting design variants of III-Nitride MQW LED, we will simulate the structure using Lumerical FDTD.

Analysis

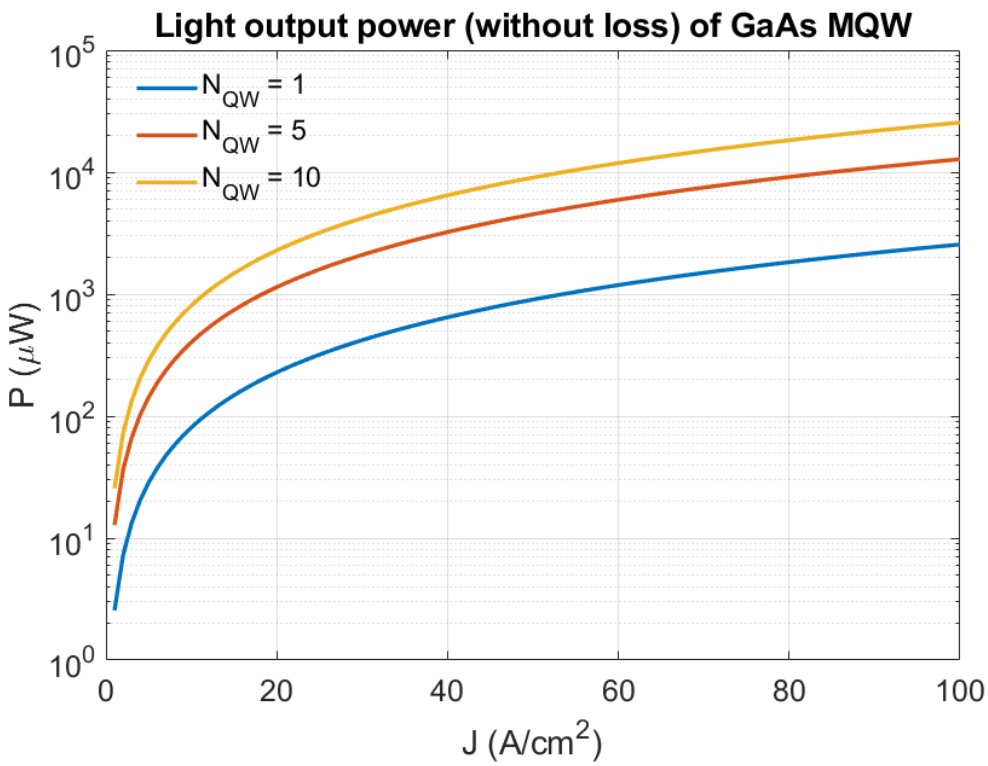
Variation of peak lambda for different QW width



The peak wavelength of the emission spectrum in GaAs multi-quantum well (MQW) structures depends on the width of the quantum wells. From the above plot, we can see that narrower quantum wells result in emission at shorter wavelengths, while wider quantum wells result in emission at longer wavelengths.

This is because the energy level spacing of the confined electrons and holes in the quantum wells is inversely proportional to the well width. As the well width decreases, the energy level spacing increases, and the emission energy becomes higher (i.e., shorter wavelength). Conversely, as the well width increases, the energy level spacing decreases, and the emission energy becomes lower (i.e., longer wavelength).

Effect on Output power for different number of QW



The output power of GaAs multi-quantum well (MQW) LEDs can be affected by the number of quantum wells in the structure. From the generated plot, we can notice that increasing the number of quantum wells leads to higher output power, up to a certain point.

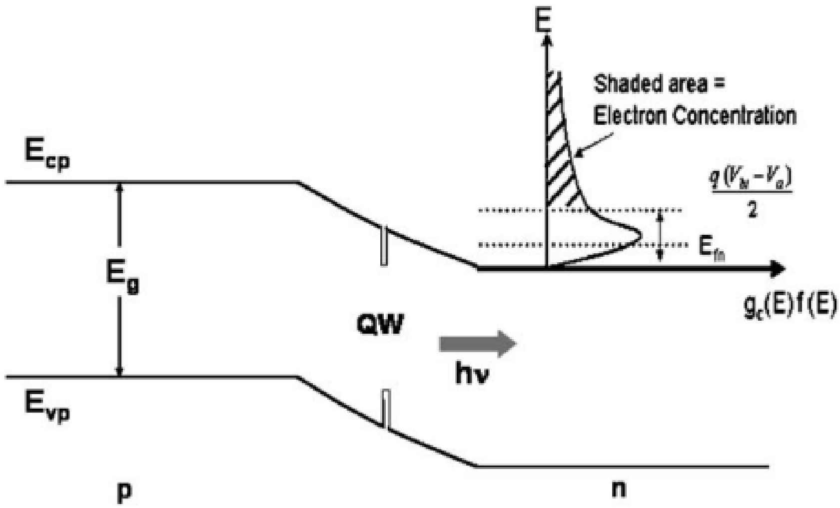
This is because adding more quantum wells increases the number of active regions where electron-hole pairs can recombine and emit light, leading to higher radiative recombination rates and higher output power. The exact relationship between the number of quantum wells and output power will depend on the specific material, structure, and operating conditions of the LED. In general, increasing the number of quantum wells from 1 to 5 or 10 can lead to significant increases in output power.

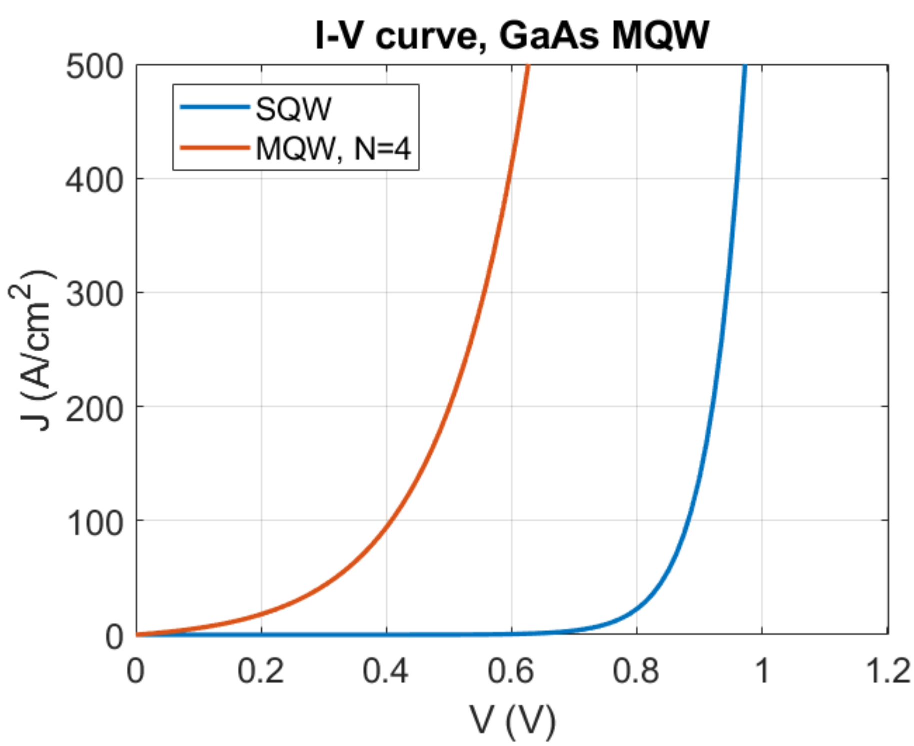
I-V characteristics

$$n_{\mathrm{inj}} = \int_{a}^{b} f(E) g_c(E)\, \mathrm{d}E, \qquad n_{inj} = \frac{m_n^* \sqrt{2m_n^*}}{\pi^2 \hbar^3} \int_{\frac{q}{2}(V_{bi}-V_a)}^{\infty} \frac{\sqrt{E-E_c}\, dE}{e^{(E-E_f)/kT}}$$

$$J_n(x) = qD_n \frac{dn}{dx} \cong qD_n \frac{n}{x_n}$$

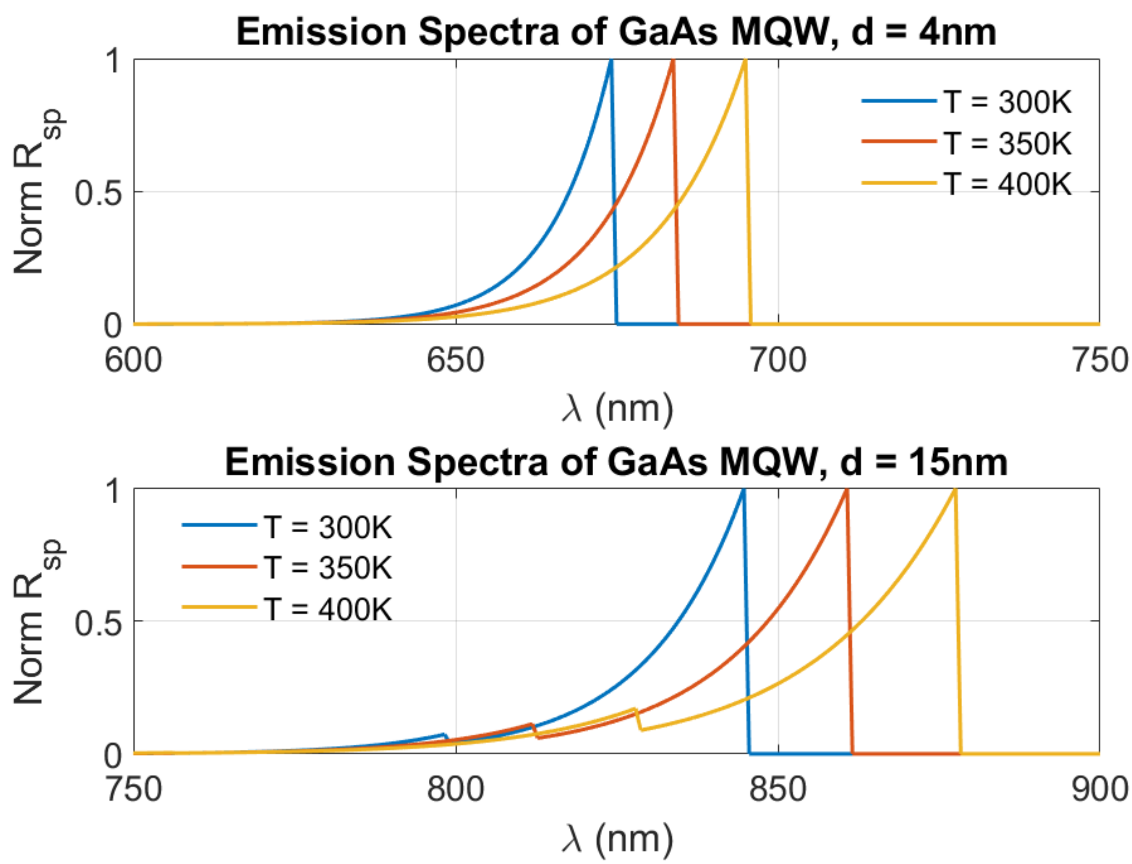
Where Dn is the electron diffusion coefficient, in units of cm2/s, xn is the depletion width on the n-side.





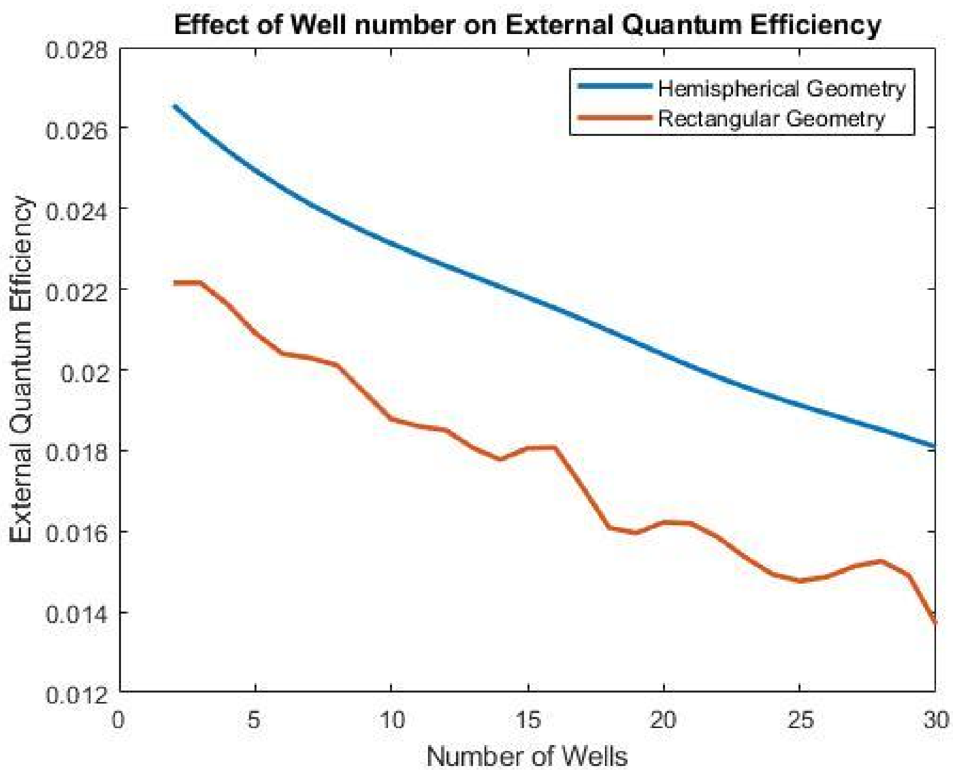
In bulk LEDs, carriers are not confined in a narrow quantum well, leading to a higher threshold voltage. In contrast, in an MQW LED, carriers are confined in narrow quantum wells, leading to a higher probability of carrier recombination and a lower threshold voltage. This effect is especially pronounced in highly doped MQW structures, where the confinement potential is higher and the Vth is lower. Moreover, the threshold voltage of an MQW LED keeps decreasing with increasing well number because the increased number of quantum wells increases the probability of carrier recombination and reduces the V_{th}. The decrease in Vth is due to the enhanced radiative recombination rate in the MQW structure, which is proportional to the number of quantum wells. The reduction in V_{th} also leads to a corresponding increase in the output power and efficiency of the LED.

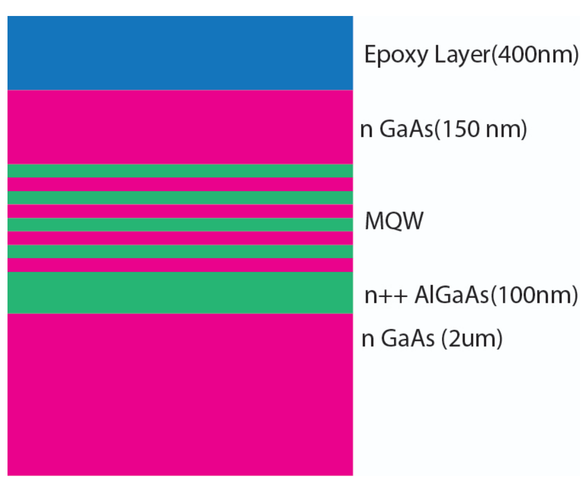
Effect on R_{sp} for different temperature



The spontaneous emission rate of a GaAs multi-quantum well (MQW) structure is affected by temperature. As the temperature increases, the spontaneous emission rate increases due to increased thermal energy and carrier density. This can be attributed to the temperature dependence of the Fermi-Dirac distribution, which describes the distribution of electrons in energy levels at a given temperature. At higher temperatures, a larger number of electrons occupy energy levels near the conduction band minimum, which leads to increased recombination rates and higher spontaneous emission. One of the primary effects is an increase in the population of thermally-excited carriers in the quantum wells, which can lead to a broadening of the emission spectra. For T= 400K, spectrum broadening is the highest and lowest for T= 300K. As the temperature of the LED increases, the bandgap energy of the materials used in the MQW structure will decrease. This reduction in the bandgap energy will cause a shift in the peak wavelength of the emitted light towards longer wavelengths (lower energy).

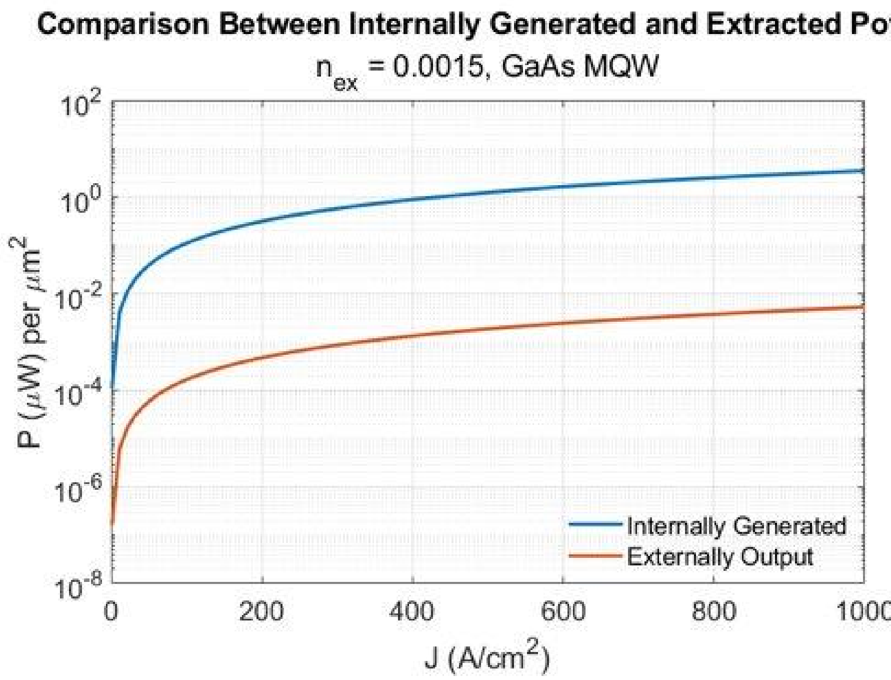
Light Extraction



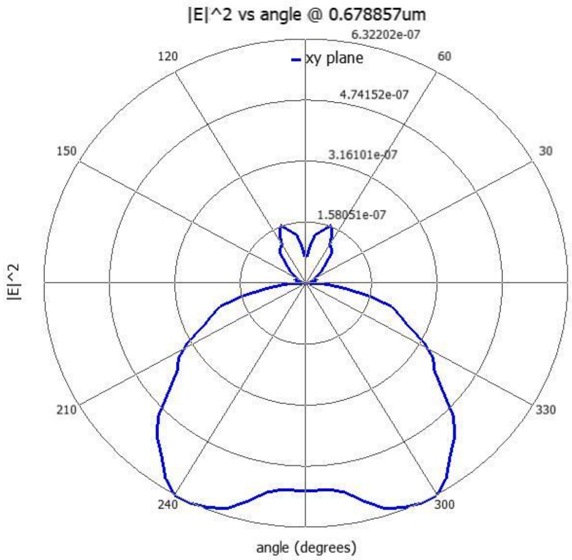


For calculating light extraction from inside the QW, we performed FDTD simulation. For this, a surface emitting LED with a hemispherical and rectangular head was analyzed. The below is a proposed figure, with GaAs well width of 4nm and AlGaAs barrier of 8nm. From simulation results performed for λ_0 = 678.6nm. Hemispherical design offers more light extraction compared to rectangular structure as expected.

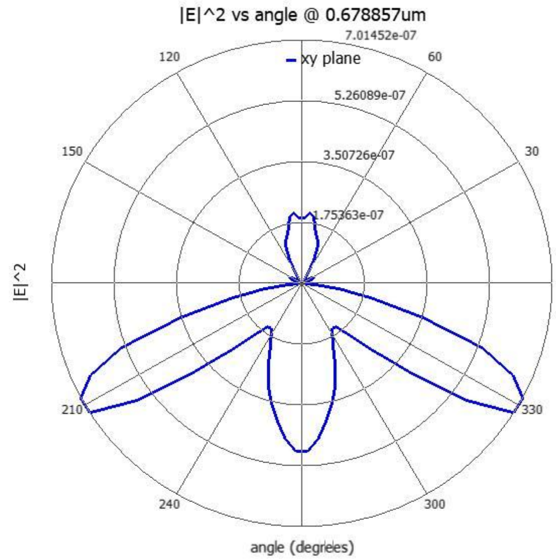
Polarization of light from LEDs is random. Z-polarized light emitted from the QW interacts with the well itself and absorption is very high for this polarization. However, x and y polarized light only encounters material absorption and thus decreases with well number. More QW simply adds more material for light to get absorbed and thus, extraction lowers. On the other hand, rectangular geometry is limited by Fresnel loss and critical angle effects, so extraction is low.



Lambertian Emission Pattern:



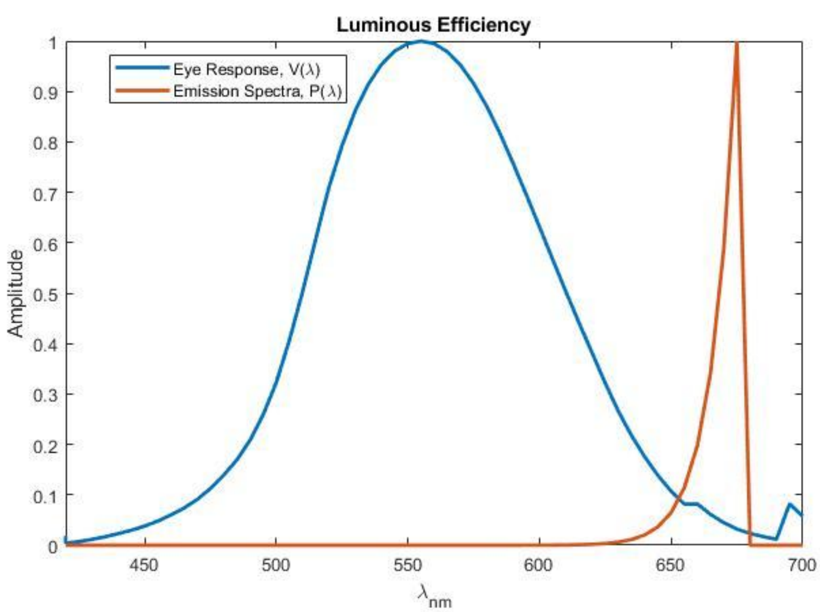
Emission Pattern For Rectangular geometry (n_{QW} = 4)



Emission Pattern For Rectangular geometry (n_{QW} = 4)

Lambertian emission pattern refers to the idealized radiation pattern of a light-emitting device, where the emitted light is uniformly distributed in all directions. In other words, the intensity of the emitted light is the same regardless of the viewing angle.

Luminous efficiency



The eye response of a GaAs MQW LED with varying wavelength can be analyzed by considering the spectral sensitivity of the human eye. The sensitivity of the human eye to light varies depending on the wavelength of the light, with peak sensitivity occurring around 555 nm (green light).

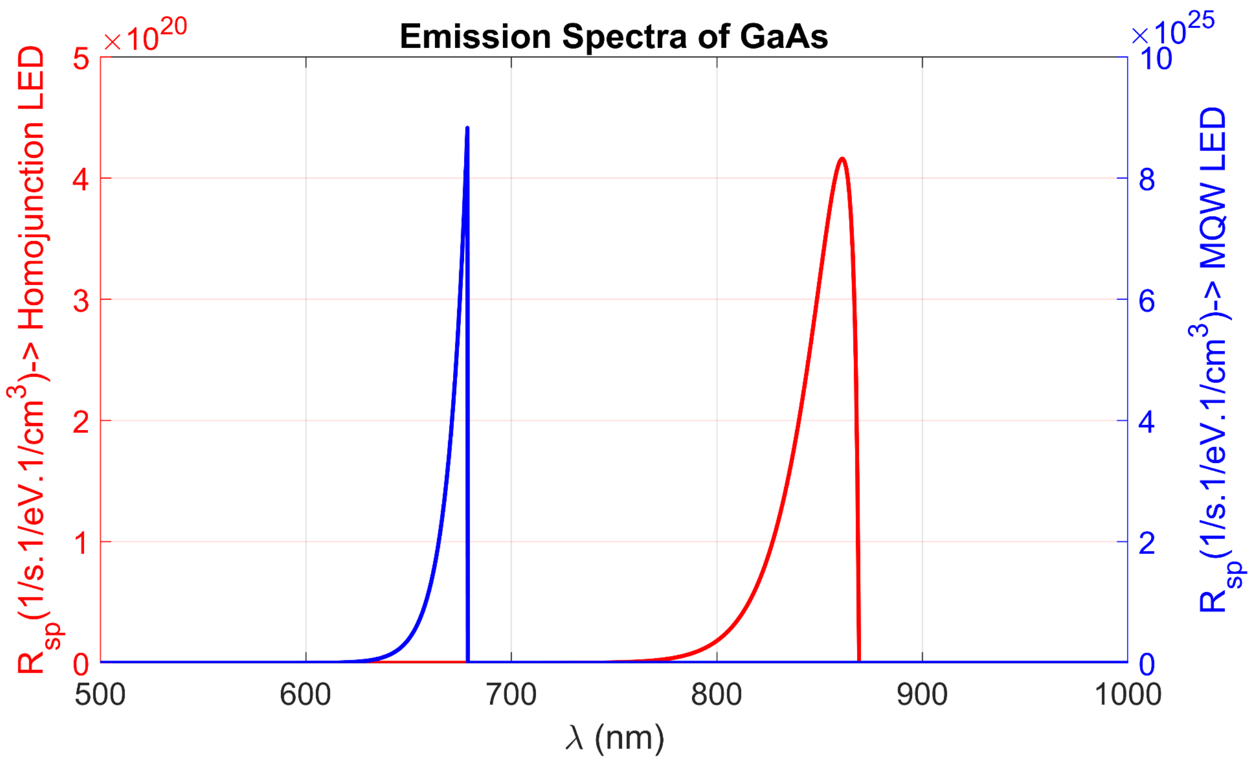
For a GaAs MQW LED emitting light with a wavelength in the visible range, the eye response will depend on the spectral output of the LED. In general, the eye response will be higher for wavelengths that are closer to the peak sensitivity of the human eye (around 555 nm) and lower for wavelengths that are further from this peak sensitivity, which is evident from the plot.

After generating eye response and emission spectra, we calculated luminous efficiency using the following formula:

$$\eta_L = \frac{\int_\lambda V(\lambda)P(\lambda)d\lambda}{\int_\lambda P(\lambda)d\lambda}$$

Our calculated luminous efficiency = 0.0532.

Comparison with Homojunction LED



Photon flux for Homojunction LED = 4.45×10^{15} s^{-1}, while for MQW LED = 4.32×10^{17} s^{-1}
For d= 4nm well width.
The emission spectrum of an MQW LED is much narrower and peaks at a specific wavelength determined by the thickness and composition of the quantum wells.By engineering the thickness and composition of the quantum wells, the bandgap energy of the material can be tuned to a much narrower range. This allows for more precise control over the peak wavelength of the emitted light.

Conclusion

In conclusion, this project aimed to investigate the characteristics of III-V MQW LED devices for visible wavelength emission. Two main objectives were set out: to analyze the effect of different parameters on the performance of III-Nitride MQW LED devices for visible wavelength emission and to analyze spontaneous emission rate and optical extraction mechanism of a MQW structure. By analyzing carrier dynamics and spontaneous emission rate, we gained insights into the efficiency of the device and the underlying physics of its operation. Overall, the project successfully achieved its objectives, providing valuable insights into the characteristics of III-V MQW LED devices for visible wavelength emission and opened avenues for future theoretical analysis.