Size Effects of Micro-LEDs on the performance of wearable displays

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Abstract

Micro-LEDs are emerging as technology of the future because of the higher quantum efficiency they can offer over the current technology which comprises of LCDs and OLEDs. This technology will have application in micro-display wearable electronics due to the higher amounts of brightness they can offer for the same power input as compared to some of the broad-area LEDs. However, within these micro-pixels, trends exist in efficiency levels when the micro-devices are scaled. For smaller micro-devices ($\sim 5\mu m$), according to the literature, the experimental efficiency levels tend to be small as compared to the micro-LEDs which are comparably larger ($\sim 100\mu m$). This is because the smaller modules undergo non-radiative combination on higher current density levels due to Auger recombination. The experimental EQE was between 12%-13% for micro-modules which were $100\mu m$ in dimension and was the highest recorded efficiency between $5\mu m - 500\mu m$ modules [3]. Literature based simulations showed a much higher level of EQE for the corresponding levels of current density as can be seen in Figure 10. The highest EQE recorded was for $300\mu m$ at about 70% [4]. Hence, it can be seen that there is a large difference between experimental and simulation-based data from literature. Thus, the processes can be improved greatly to improve the experimental EQE of the micro-displays. The maximum EQE also tends to increase with the increase in size of the chip for the simulation which confirms the experimental data to be accurate.

The result of simulation generated from simuapsys.exe is not very accurate because of the flaws in the model that is generated and a failure to generate a rectangular 3-D structure. However, the result of the IQE vs. current density plot (Figure 14) agrees with the plot in Figure 8(for the optimized manufacturing process). Hence, it can be seen that simulations conducted from crosslight are consistent with the ones obtained experimentally in terms of the shape of the curves. However, the trends relating to the sizes are not consistent, showing the inconsistency of the simulation done through simuapsys. Thus, there is a need for extra software applications such as Semicrafter and CSUPREM to model this LED in three dimension as a cuboid and conduct more accurate simulations.

Motivation

Broad-area conventional LEDs have been dominating the market in term of the applications in various areas such as lighting, displays and in medicine. However, the high-power consumption (or the low efficiency) and the high cost of these LEDs make the discovery of alternatives extremely important. The discovery of OLEDs has enabled thinner, lighter and more flexible crystalline layers than the LEDs and are brighter than the conventional LEDs [1]. However, OLEDs use organics, and tend to degrade over time in terms of the color-shift that is observed. Micro-LEDs offer a potential solution to these problems faced by the existing LED technology used for various applications. At present, there are several manufacturing issues that are barriers to current usage in various applications. Nitride-based micro-LEDs offer higher efficiency, high reliability, long lifetime and low power consumption and hence can be used for better power efficient applications by connecting them in parallel. The other application is for highly efficient and electroluminescent displays. Due to the multiple quantum-wells enveloped by the p, n-doped layers, the micro-LEDs offer a narrow emission band of 25nm which translates into better chromatic fidelity [2]. Broadly, III-nitride micro-LEDs are divided into two segments. The first category utilizes the recombination from the MQW (Multiple Quantum Well) to emit light and have p-bus and n-bus in the same plane and other one known as the flip-chip system utilizes the vertical p-bus and n-bus configuration.

In this project, the emphasis is laid on the blue micro-LED technology emitting at 440nm which is used in almost every micro-display for wearable devices. The scaling effects of the blue micro-displays generating in the InGaN/GaN MQW has been of special interest due to the higher efficiency of the displays along with greater brightness of the displays. Gallium Nitride based micro-displays have been used in a two-dimensional array where the micro-LED serves as a single pixel of the display. Recent experimental developments have seen 873*500-pixel micro-displays of 10 μm in dimension functioning at very high brightness levels [3]. These devices tend to have a very contrasting behavior to the larger high-power devices. Micro-displays work on very high current density levels and because of this can showcase strong thermal and non-thermal droop of the micro-LED efficiency. This is largely caused by the Auger recombination which can limit the device performance significantly. In small LEDs, surface recombination, at the edge of the active region causes electron and hole losses. Thus, carrier losses, which are responsible for the loss of the intensity of light, depend on the size of micro-LEDs. Current crowding effects are also responsible for the efficiency droop due to strong current localizations [4].
Thus, it can be observed that there is a problem in the micro-LEDs for wearable devices. This problem entails the determination of the size of the LEDs and how this impacts the properties of the LEDs. Blue-LEDs are a great subject to study because of their popularity in various applications and their

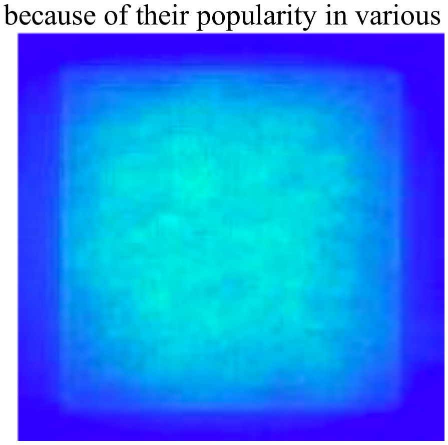

Figure 1. *Optical Image of a 50 μm *50 μm LED operating a high current density [3]*

predominant use in the wearables. This study is conducted by computational tools in order to determine the maximum efficiency levels as they disregard the current manufacturing issues. With the optimized manufacturing processes, the results obtained from the simulations can offer an insight into the trade-offs that are involved in using different technologies. It can serve as an indicator of how cost effective and energy effective these micro-displays can be made in comparison with the existing LCD and OLED technology.

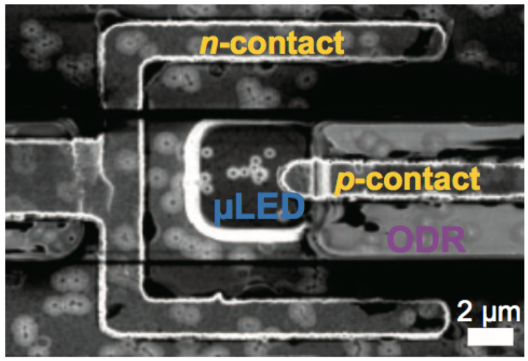

*Figure 2. Electron microscopy image of a 5 µm*5 µm micro-LED [5]*

To date, the micro-LEDs have been scaled down to 5 μm. The cross-section of one such LED is shown in Figure 2 under the electron microscope and shows how the micro-LED is arranged along with the contacts. The micro-LEDs have shown significant drops in quantum efficiency levels when they are scaled to such dimensions. There are also issues with nitride based micro-LEDs because of their poor conductivity and optical absorption. These issues are also a great subject of study. However, this study will lay focus on the size as the design focus and how it will impact the market penetration of the micro-LEDs in the future.

Introduction and Background Physics

On a basic level, LEDs are made of heterojunction semiconductor and insulator layers stacked on top of each other. However, the light is emitted due to the quantum effects seen within the semiconductor layers. In intrinsic semiconductors the electrical conductivity and hence the optical generation is not possible due to the valence band being packed with electrons. When, the semiconductor has electrons in the conduction band, it is possible for the electron to descend from the lowermost layer of the conduction band and combine with a hole in the valence band. This process of electron-hole recombination is the reason for emission of a wavelength that may or may not be visible. LEDs utilize materials that emit energy of the range of the visible spectrum of light. The recombination that is described above is given in Figure 3. An InGaN/GaN Quantum well LED utilizes this principle as well. The whole structure is built on a sapphire substrate with a p-layer and a n-layer which encompasses the MQW structure. In this MQW the recombination takes place and hence, by changing the composition of the InGaN MQW structure and fixing the length of the MQW structure, the emission wavelength can be controlled [6]. The recombination takes place due to the flow of current between the contacts, thereby causing the recombination to take place and emit light from the MQW layers. A heterojunction device such as the InGaN/GaN MQW LED, generally has two or more materials which have different bandgaps. Hence, by controlling the material band-gap, the flow of charges and hence the recombination can be controlled. Since, wide-bandgap materials are transparent to the photon re-absorption, the heterojunction devices are used instead of the homo-junction devices because heterostructure devices have greater radiative efficiency due to a greater flow of current [7]. The idea of using MQW LED is very important to explore.

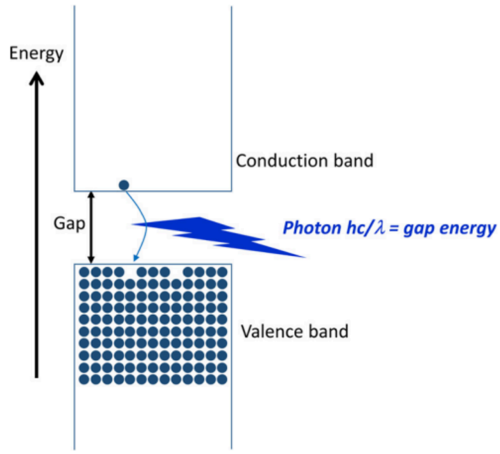

Figure 3. The recombination process due to an electron-hole pair causing the emission of a photon [6]

The MQW structure allows the motion of electrons to be affected by the quantum interference due to the thin heterostructure layers. The MQW region is likely to have thin layers of narrow band-gap materials and thick layers of wide band-gap materials. This allows the band to attain a rectangular quantum well profile. These MQW structures are key to optoelectronic devices because they are able to confine the charge carriers to small regions, there-by boosting the electro-optical interactions [7]. The electrons and holes are confined to narrow quantum well places and are confined to discrete energy states. This recombination in discrete energy states leads to a narrow emission spectrum. Also, due to increased number of quantum wells, there is a greater chance for the carriers to recombine.

Efficiency droop is a very important parameter when defining the merits of a heterostructure LED. Droop is a result of high current densities decreasing the efficiency of the LEDs. This efficiency is known as internal quantum efficiency (EQE) and is dependent on radiative recombination rate and non-radiative recombination rates. The equation for internal quantum efficiency is given in Equation 1 [8]. This equation has the radiative recombination rate given by the term Bn^2 and non-radiative terms given by An and $Cf(n)$. Hence, the requirement in LEDs is to maximize the radiative recombination term and minimize the non-radiative terms. This is due to radiative recombination resulting in optical generation where-as non-radiative recombination results in heat energy. The n used in equation 1 shows the carrier density.

$$\eta_{IQE} = \frac{Bn^2}{An+Bn^2+Cf(n)} \tag{1}$$

Auger-recombination is an event when $f(n)$ is n^3 and leads to dissipation of heat as a non-radiative recombination mechanism. In this mechanism, the electron-hole recombination excites another electron instead of emitting a photon. This electron, also known as the Auger electron, has kinetic energy transferred into it and is dissipated as heat and the electron flowing out of quantum well leading to current leakage [8]. This mechanism has significant impact on the efficiency of the LED.

Micro-LEDs, specifically work on high current-density and hence there is a need to understand the effect of size on how the current density changes. This effect is also key to understanding the effects of size on the efficiency of the LED modules. LEDs that are small in size have a significant drop in efficiency due to Auger recombination. Auger recombination leads to both thermal and non-thermal droop. Surface recombination at the edge of the active region also leads to the loss of carriers as the size of LED is decreased [4]. Current crowding in micro-displays can be a significant cause of the drop of efficiency. Figure 4 describes the difference in the radiative recombination and Auger recombination. In radiative recombination, as can be seen, the electron-hole recombination is causing the emission of photon. However, in Auger recombination, the electron is emitted due to the electron-hole pair recombination. In case of indirect Auger recombination, there is also emission of phonons.

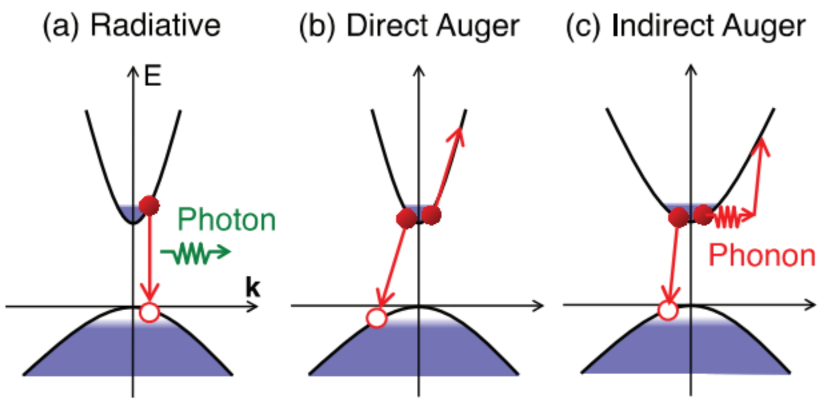

Figure 4. The schematic representation of the difference in Radiative and Auger Recombination [9].

The radiative recombination needs to be enhanced to make the micro-display device highly efficient. This recombination rate as can be seen from Equation 1 has a coefficient B which is given by the division of spontaneous recombination rate and the product of unit volume and carrier density squared. This is given by Equation 2 [9].

$$B = \frac{R_{sp}}{n^2 * V} \tag{2}$$

When the coefficient for radiative recombination is plotted as the function carrier density it shows a result given in the plots in Figure 4. for GaN and InGaN which are the two key compounds of the micro-LED under study. This is key in understanding the doping concentration for the layers of micro-display that are required to give a certain amount of spontaneous emissions.

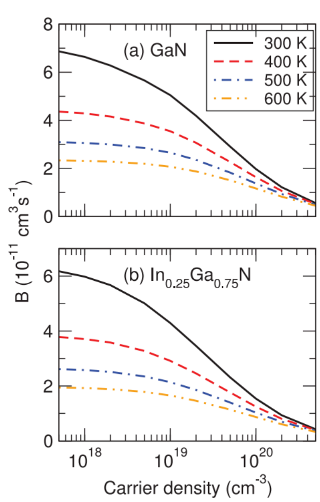

Figure 5. The plot for B as a function of carrier density

Design of the Experiment on LEDs

The lateral structure of the of the micro-LED built for simulation purpose is shown in Figure. 6 [10]. A similar structure to this one is used for simulating the size effects except the unintentionally doped GaN layers. These layers are ignored for simulation purposes because these layers are not responsible for recombination mechanism. The spreading layer is ignored as well. The layer that is also included between the p-GaN and MQW region is the electron blocking layer (EBL). This layer is responsible to prevent the decomposition of the InGaN quantum wells.

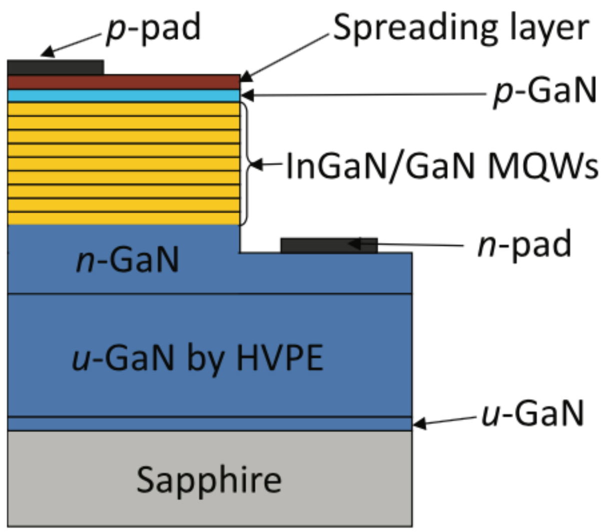

Figure 6. The hetero-structure of "a pixel" of a micro-display

The layers of the structure that is prepared for simulation is given in Table 1 [4]. This table encompasses the material, the doping concentration and the thickness of the layer.

Table 1. The table of the components of the micro-LED and their thickness and doping concentrations

Layer	Thickness (nm)	Doping (cm^{-3})
n-GaN cladding layer	5000	$5 * 10^{18}$
5*(2.7 nm InGaN/7nm GaN)	41.5	Undoped
p-GaN	8	$0 - 2 * 10^{19}$
p-AlGaN EBL	20	$2 * 10^{19}$
p-GaN cladding layer	180	$5 * 10^{19}$

The layer is built on an application of Crosslight called Simuapsys.exe. This program enables the building of a stacked LED or any quantum-mechanics device. This LED structure needs a mesh construction on top of it for the ability of solution of various properties of the device being simulated. If the number of meshes is increased, then the solution to the various properties of the device is more accurate. However, there is a loss of speed in the simulation of the device. Because of the complications of controlling all 3 dimensions in crosslight, the thickness of one side is kept constant due to the fixed measurements in Table 1. On another direction is the variable size, which is varied to test the size effect on the efficiency on the LED. The third direction is kept constant with a length of 1 μm.

The initial experiment was done to simulate the effect of the number of quantum wells and hence the thickness of the device, to see the effect on the I-V characteristics and efficiency levels of the device. The second experiment was the change in the size (length) of the device and test its impact on the internal quantum efficiency (IQE) and the I-V characteristics. The data set in the first experiment was collected for quantum wells from 2-7 in number. The data set in the second experiment was collected for 8 data sets which are for the following lengths: $5\ \mu m, 10\mu m, 15\mu m, 20\mu m, 50\mu m, 100\mu m, 200\mu m, 500\mu m$. The AlGaN used as EBL had the composition value $x = 0.15$ and the InGaN layer used in the quantum well had the composition value $x = 0.18$ for emitting 440nm specified blue light wavelength [4]. In the solution file the Auger coefficient used was set to $2.0 * 10^{-30} cm^6 s^{-1}$[11]. The .plt file was modified in such a manner, that the data for band diagram, I-V curves and efficiency curves were obtained and the data was exported by giving the command to store as a .csv file which exported the data to excel.

Theoretical Results & Discussion

In general, the micro-LED has various parameters that are affected by the variations in the size. However, the two most critical parameters are EQE and IQE which define how efficient the output of the LED is. First let us take a look at the I-V characteristic plot displayed by a micro-LED due to experimental testing and not simulation-based testing. This gives an idea of the device's performance in the non-ideal/real conditions. The I-V plot is displayed in Figure 7. shows the active region for the diode in the first quadrant which is typically by LEDs [3].

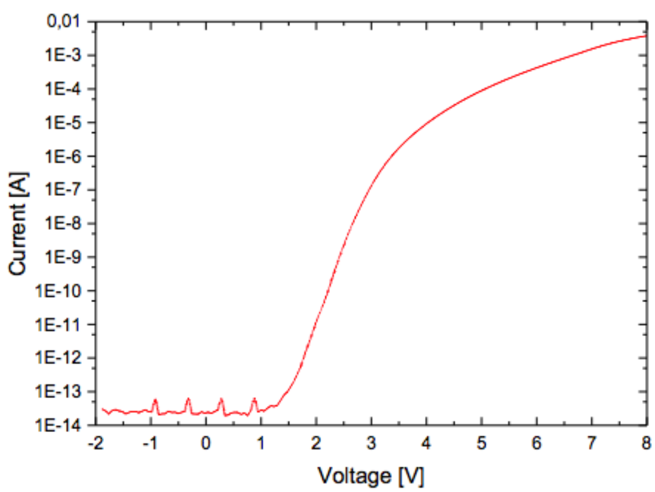

*Figure 7. The I-V plot for a 7 μm*7 μm micro-LED module*

The I-V plot shows a very ideal characteristic. The process used in the experimental technique sees the change of etching process and due to the p-contact having higher reflectivity and lower contact resistance [3]. This reduces the loss due to current leakage and hence the plot in Figure 7 achieves ideal characteristic. The same experimental result also gives the plot for EQE to be the one shown in Figure 8. [3]. The plot which is labelled as "optimized process" is the one that is considered because it is the method that gives a more ideal plot. As we can see that the efficiency value increases to a maximum value and stabilizes for high value of current density (and only decreases marginally).

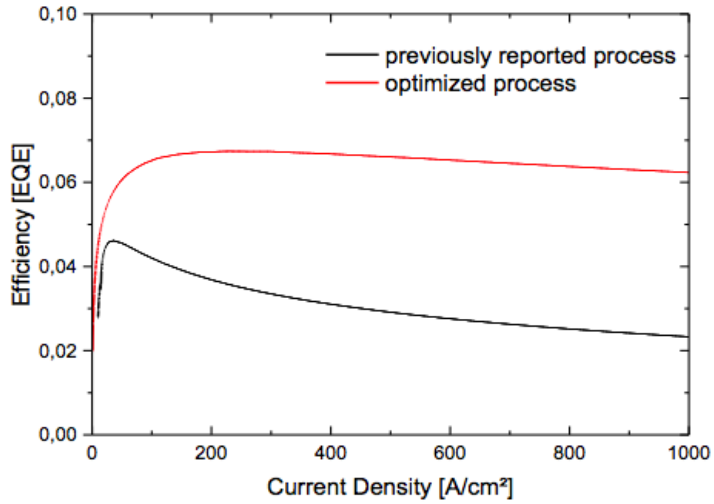

*Figure 8. The EQE vs. Current Density plot for a 7 µm*7 µm micro-LED module*

The EQE plot in Figure 8. Is also a fair representation for the IQE because EQE is essentially a function of IQE [12]. Equation 3 gives the relation between EQE and IQE.

$$\eta_{EQE} = \eta_{IQE} * \eta_{Extraction} \tag{3}$$

Thus, any internal quantum efficiency plot would be a function of the external quantum efficiency and would look same if the extraction efficiency is 1. Since, the luminance increases with the increase in current density, Figure 8 shows that higher quantum efficiency can be extracted at high current densities for micro-display devices and hence these devices tend to be brighter. In general, the maximum EQE achieved by the micro-LED, experimentally, is between 12-13% [3]. The resulting graph for the 8 data values that were also chosen for the simulation values is given in Figure 9 which is based on the experimental results.

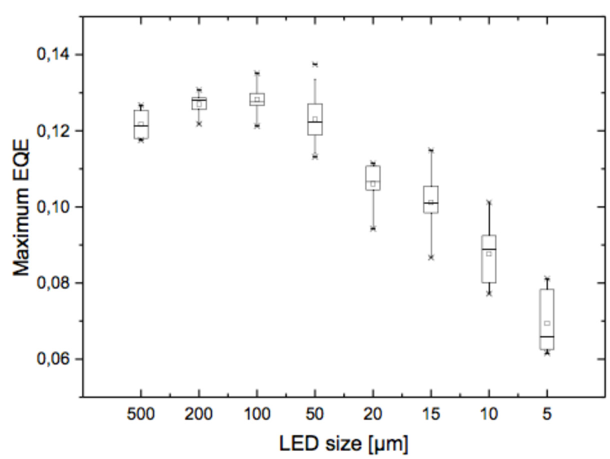

Figure 9. The EQE vs. LED size plot for micro-LED modules of varying size

The plot in Figure 9 shows that for smaller sizes the EQE value is very low and increases as the size is increased. The low EQE value for small pixel values can be attributed to the increase in non-radiative recombination in the P-GaN region. In this region, the carriers are lost thermally before they are able to reach MQW structure [3]. As the size is increased the number of carriers that are able to reach the quantum wells increases. This results in the increased external quantum efficiency as the size is increased. However, at higher sizes ($\sim 200\mu m - 500\mu m$) the quantum efficiency tends to decrease. Hence, there is an optimal size of $100\mu m$ at which the micro-LED module maximizes the efficiency. The deduction from this plot is that the efficiency is lower for lower sizes because of more non-radiative recombination at lower sizes [3].

The EQE for the simulation-based result for varying mean current density and diameter for the chip is given in Figure 10 [4]. This shows that the mean current density causes the EQE to increase and then starts decreasing for very high values of mean current density levels because of non-radiative recombination taking place at higher densities. It can also be observed that the maximum EQE increases as the chip diameter is increased and hence the pixel size should be kept relatively high for obtaining high brightness. This trend is shown In Figure 11 [4].

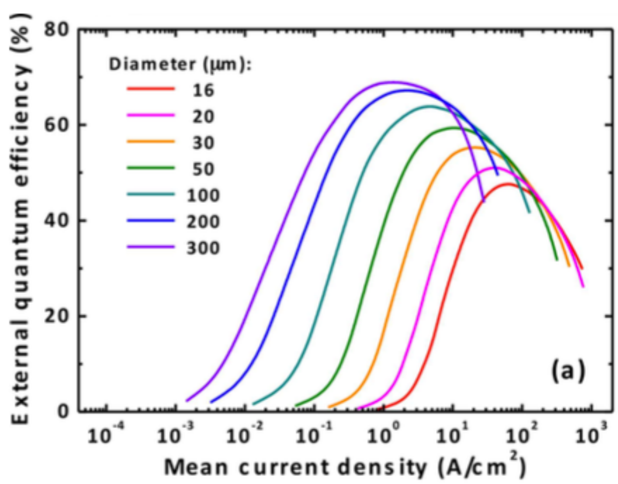

Figure 10. The EQE vs. mean current density plot for micro-LED modules of varying diameters

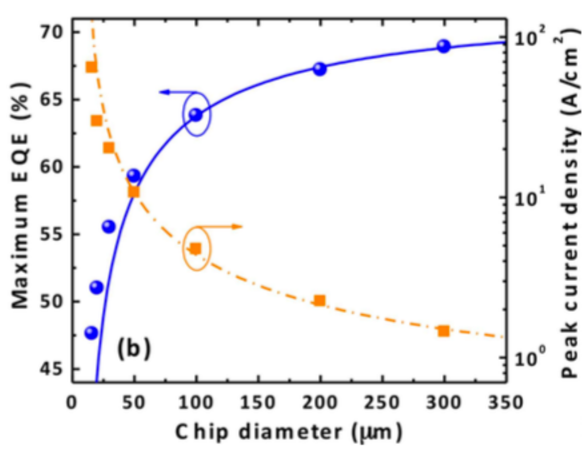

Figure 11. The EQE vs. LED size plot

Simulation Based Results & Discussion

As seen before, the literature-based results are due to two-dimensional size variation. The simulation-based experimentation conducted with crosslight software was based upon one dimensional size variations. The first experiment conducted by varying the number of quantum wells and hence the thickness of the total MQW region. As can be seen, the EQE does not vary significantly due to the Current density from Figure 12.

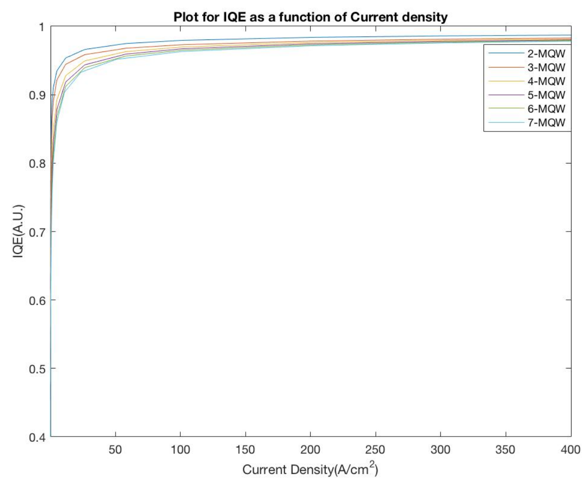

Figure 12. The EQE vs. Current Density plot for varying number of MQW

There is no significant variation in the quantum efficiency due to the variation of the thickness of the size of the MQW region. Thus, for the experiment we use 5 MQWs as given in the literature [4]. However, it can be observed that lesser number of quantum wells in the MQW region leads to the increase in the spontaneous emission rate as can be seen in Figure 13. Hence it leads to increase in the number of radiative recombination in the lesser number of quantum wells due to the carriers being able to pass through the MQW region.

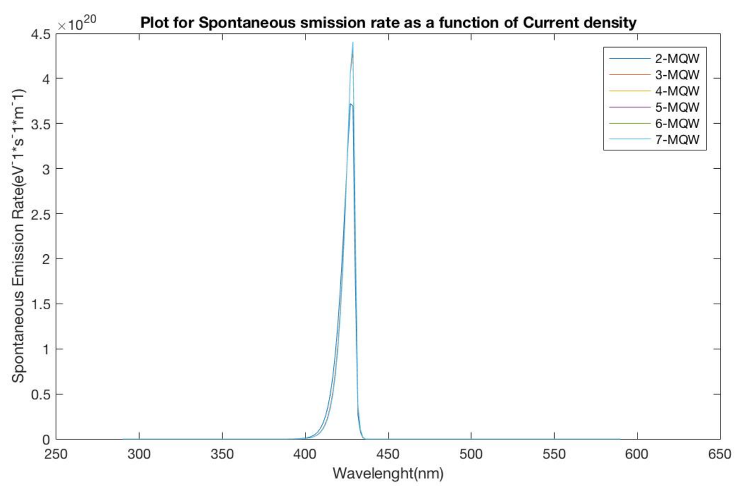

Figure 13. The Spontaneous Emission Rate vs. Wavelength plot for varying number of MQW

The second simulation set was conducted for the change in the dimensions along the micro-pixel in one direction and observe the effects of this change. From theory studied before, the quantum efficiency increased as the chip-size of the micro-display was increased. Figure 14 shows the plot for the IQE as a function of current density.

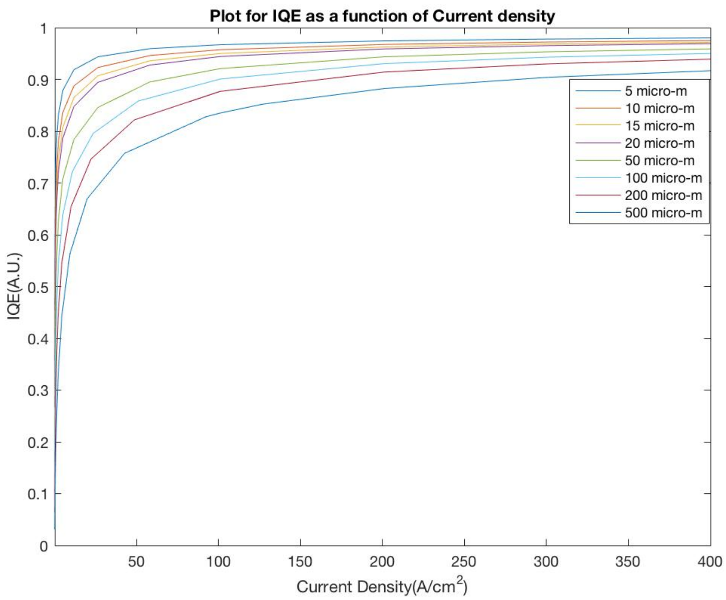

Figure 14. The IQE vs. Current Density plot

The plot in Figure 14. shows the result to be opposite than that of Figure 10. The plot in Figure 14. shows that the largest LED has the least efficiency level. This does not conform with the data that was simulated before in Figure 10. but it conforms with the data from Figure 8. for optimized process which shows the lack of actual dependency of IQE on current density after a certain value of current density. There is no significant difference between IQE in Figure 14. for higher current density values. Peak IQE values should be higher from the larger micro-LEDs than the smaller ones which means that the simulation in two dimensions failed the literature values that were observed because the three-dimensional non-radiative recombination for the smaller LEDs were not accurate in the simulation. Also, the size of third dimension is kept constant and to a very low value and hence it effects that inaccurate results obtained in Figure 14.

Conclusion

Micro-LED displays are on the verge of reforming the display industry due to their efficiency levels. These displays have extensive applications in wearables for providing brighter light emission from the pixels. The size of each pixel effects the efficiency at which the LED emits. This is because the non-radiative recombination becomes very active at very small dimensions of the micro-displays. At larger sizes there are lesser non-radiative recombination as compared to the radiative recombination rate. By using Equation 1 the effect of various recombination rates and their effect on efficiency can be determined. Due to Auger recombination (non-radiative), the decrease in efficiency tends to be significant in smaller LED modules. Thus, the challenge is to ensure that the non-radiative recombination is decreased significantly in comparison with the radiative recombination.

The application used to measure the quantum efficiency for the MQW was SimuApsys.exe and was used to simulate a 2-D LED module. There size of the LED was changed by changing the number of quantum wells in the MQW structure. This did not cause significant changes in the efficiency of the module but caused the module to change in terms of spontaneous emissions which was higher for lower number of quantum wells in MQW region.

For the simulations on MQW LED for changes in the size of the micro-LED pixel in one dimension, the quantum efficiency trends were opposite than that of the ones obtained in the simulation based and experimental data obtained from literature. With the help of the applications of crosslight known as Semicrafter and CSUPREM, the simulation can be conducted with a three-dimensional rectangular model which would enable to obtain accurate trends.

This would enable the accurate development of the micro-LED modules which would be better than the OLED and LCD technology that exists in the wearable technology, currently.

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