Designing Efficient Micro Light Emitting Diodes for Display Applications

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Abstract

Demands for high performance displays have risen due to applications ultra-high definition TV's, mobile/wearable devices, AR/VR displays and more. Current display technology such as OLED and LCD have some limitations that prevent the best possible experience for uses. Micro light emitting diodes (LED) have become a strong contender in next-generation displays they have some advantages compared to LCD and OLED. Micro LED can achieve higher peak brightness, better color accuracy, faster response times and are more reliable; however one undesirable effect of scaling down LEDs for display applications is the decrease in efficiency. The decrease stems from non-radiative recombination in defect centers on damaged sidewalls. As the micro-LED is scaled down, the ratio of the sidewall recombination to bulk radiative recombination increases, hence, decreasing the efficiency of micro LEDs. Through TCAD simulation done in Crosslight APSYS, behavior of micro LEDs as they are scaled down is investigated in this report in order to design efficient micro LEDs for display applications. It is found that surface effects contributes to rapid decrease in peak IQE for sizes less than 50um, reducing from a peak of 74% at 500um to a mere 17.2% at 2um. With surface treatments, this effect can be reduced; when no surface non-radiative recombination is present, scaling does not decrease peak IQE, however droop becomes more significant as size of the LED is reduced. Effects of quantum well thickness and period for 10um micro LEDs is also investigated in order to optimize the design. It is found that 2 QW periods has the least droop and 3 QW periods is a good compromise between peak IQE and droop. For QW thickness it is found that 5nm resulted in the best peak IQE, however thicker QW showed better droop performance. By optimizing its size and structural design, micro LEDs have been to shown to be a strong contender in next generation display technologies.

Introduction and Motivation

Light emission from solid state materials when electricity is applied has been observed since the early twentieth century[1], since its discovery tremendous progress has been made in the field of semiconductor photonics. The first practical light emitting diode (LED) was demonstrated by Holonyak and Bevacqua in 1962[2] and later, through the work of Akaski[3] et al. and Nakamura[4] et al. high brightness blue LEDs became possible. From original uses of low brightness red/infrared LEDs for signaling and signage to lighting applications with high efficiency and high brightness LEDs to high-speed optical interconnects for data communications, LEDs have certainly become an integral part of our modern lives. One other use of LEDs is in display applications; although early applications was developed as early as 1968 by Hewlette-Packard[5,] the applications were limited to simple numerical displays that were not high resolution. Not long after, a new display technology emerged that practically replaced early LED displays[5]; liquid crystal displays (LCDs) are still one of the most popular display technologies today and have become quite advanced. Over the years, many other technologies such as CRT, plasma, e-ink have come and gone;

increasing demands in performance such as improved efficiency, color accuracy, pixel density and novel applications have led to the development of many new display technologies.

Next generation and even modern display technologies are incredibly demanding due to applications in ultra-high-definition televisions, mobile phones/wearable devices, virtual/augmented reality displays and more. Requirements of these displays include but are not limited to "1) high dynamic range and a high ambient contrast ratio, 2) high resolution density 3) wide color gamut, 4) wide viewing angle and an unnoticeable angular color shift, 5) fast motion picture response time to suppress image blur, 6) low power consumption, which is particularly important for battery-powered mobile displays, 7) thin profile, freeform, and lightweight system, and 8) low cost."[6] Currently two mainstream technologies for demanding display applications include liquid crystal displays and organic light-emitting diodes[6,7], however micro light-emitting diodes is emerging as a strong contender for next-generation display applications. This project aims to investigate and design micro-light emitting diodes for next generation displays through Crosslight simulation. By understanding the parameters and designs that makes a suitable micro-LED for display applications, more and better UHD-television, virtual/augmented reality, and portable/wearable devices can be realized.

Liquid crystal displays are one of the most common displays, they are not self-emissive like micro LED or OLED, but, they are one of the most mature display technologies. The basic structure of a liquid crystal display is composed of a backlight (commonly white LED), polarizer, liquid crystal layer, color filters and an analyzer layer. Light passes though the layers and as the liquid crystal layer is modulated by an electric field, light is either blocked or let through. Due to its architecture, there are inherent limitations such as switching speed, output brightness and efficiency. On top of the LED light source, the filter layers and liquid crystal layers cut peak efficiency and limit the typical contrast ratio to about 5000:1[7]. Contrast can be improved through zoning by using mini-LEDs for small area backlight, however LCDs still have drawbacks compared to self-emissive displays such as OLED or micro-LED.

Organic light-emitting diodes (OLED) are stacks of organic material between an anode and cathode. When holes and electrons are injected into the organic material, they recombine, much similar to inorganic semiconductors, to produce light. OLEDs have benefits of self-emissivity and can be manufactured with roll-to-roll technology. This means that it can be used in flexible applications and see-through displays. Due to its self-emissive nature, OLEDs can achieve an infinite contrast ratio and good color accuracy. OLED is currently used widely in mobile devices and high end displays that require color accuracy such reference monitors used in media productions.

Display Technology	LCD	OLED	μ-LED
Mechanism	Backlight	Self-emissive	Self-emissive
Contrast ratio	5000 : 1	∞	∞
Lifespan	Medium	Medium	Long
Response time	Ms	μs	ns
Operating temperature	−40 to 100 °C	−30 to 85 °C	−100 to 120 °C
Power consumption	High	Medium	Low
View angle	Low	Medium	High
Cost	Low	Medium	High

Table 1: Comparison of key metrics for different display technologies [8]

Although OLED and LCD are both promising they have some drawbacks. For non-self-emissive displays like LCD, it is difficult to achieve high contrast ratio and color accuracy, techniques have boosted high performance LCDs to a contrast ratio of over 1,000,000:1 however achieving true black is still difficult. OLED on the other hand can achieve good color accuracy and infinite contrast ratio however, peak luminosity is lower than that of LCDs and micro-LEDs. Furthermore, OLEDs can suffer from degradation due to its organic nature compared to its inorganic counterparts. Some of the other main parameters important for display applications are shown in table 1 above. Micro LED is a strong contender to solve some of these issues including pixel density, peak brightness, and color accuracy that LCD and OLED have, however it is more expensive due to its immaturity. It has some technical challenges one of which is scaling effects due to surface related non-radiative recombination which will be explored in more detail.

Technical Background

A basic light emitting diode consists of a semiconductor p-n junction or QW/MQW sandwiched between a p-n junction. Through electroluminescence, light is emitted when a voltage is applied across the device. The voltage applied injects electrons and holes into the active region, when the electrons and holes recombine radiatively, they emit light. With heterostructures (and QWs) carriers can be confined and made to recombine more efficiently. Figure 1 shows a simple band diagram of 2 QWs confining carriers and when electrons and holes recombine, it emits light with a corresponding energy, hv. Depending on the bandgap of the material in the QW, the emission wavelength of the LED changes. Micro LEDs have the same working principle as regular LEDs however, due to their size being scaled down, surface and other scaling effects become more important.

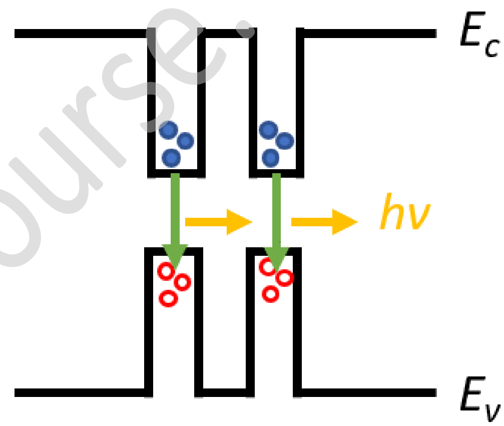

Figure 1: Band Diagram of 2 QWs, recombination of carriers results in emission of photons

When excess carriers are injected into an LED, they recombine via various mechanisms. The total recombination rate is the change of electron and hole concentration and can be written as equation 1. R is the recombination rate, n and p are the electron and hole concentrations, Δn is the excess carrier concentration and A,B,C are the Shockley-Reed-Hall, radiative and Auger recombination coefficients.

$$R = -\frac{dn}{dt} = -\frac{dp}{dt} = A\Delta n + B\Delta n^2 + C\Delta n^3 \qquad Equation\ 1$$

The radiative efficiency of a LED can be written as the ratio of the radiative recombination rate to the total recombination rate. The ABC model expresses IQE in terms of the 3 different types of recombination as written in equation 2.

$$IQE = \frac{B\Delta n^2}{A\Delta n + B\Delta n^2 + C\Delta n^3} \qquad Equation\ 2$$

The IQE can also be written in terms of the lifetimes of recombination for the radiative and non radiative processes. τ_{nr} and τ_r would be the non-radiative and radiative lifetimes, we then can then write the internal quantum efficiency η as equation 3.

$$IQE = \eta = \frac{\tau_r^{-1}}{\tau_r^{-1} + \tau_{nr}^{-1}} \qquad \text{Equation 3}$$

Non-radiative recombination can occur at semiconductor surfaces, this is due to perturbations to the periodicity of the semiconductor crystal lattice[1]. The perturbation of the lattice can result in defects and dangling bonds, these result in states within the band gap which act as centers for non-radiative recombination. In a bulk semiconductor, assuming injection is uniform (either by light or electrically) there will be a uniform distribution of carriers in space; however if a surface is present with leakage or trap states, there will be a current density flowing towards the surface. The surface recombination will contribute to the overall non-radiative rate. As LEDs are scaled down, this current flow towards the surface can start to deprive the active region of carriers and reduce the overall effieincy.

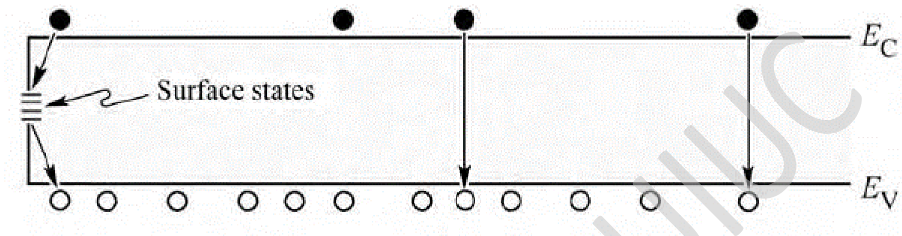

Figure 2: Surface states resulting in non-radiative recombination (figure from Light-Emitting Diodes[1])

As we scale LEDs down, surface effects becomes increasingly important due to the fact that surface area to bulk volume ratio increases. Processing and etching of the LED mesa to produce micro-LEDs damages the surface and creates the aforementioned surface states that can cause non-radiative recombination. If surface effects are no present, scaling will not change efficiency because bulk non-radiative recombination will scale with the LED accordingly. However if surface effects are present, scaling down will enhance these effects. This can be understood trough dimensional analysis: surface area scales with L^2 and volume scales with L^3. The surface to volume ratio scales as L^{-1}, it is observed that when the size is large, the surface effects don't really matter, however for small L, the ratio is greatly increased. This is shown nicely in figure 3 reproduced from Kuo[9] et al., the useable area with a fixed surface damage depth decreases as size decreases. As the proportion of non-radiative recombination due to surface effects increase, the IQE of the micro-LED decreases.

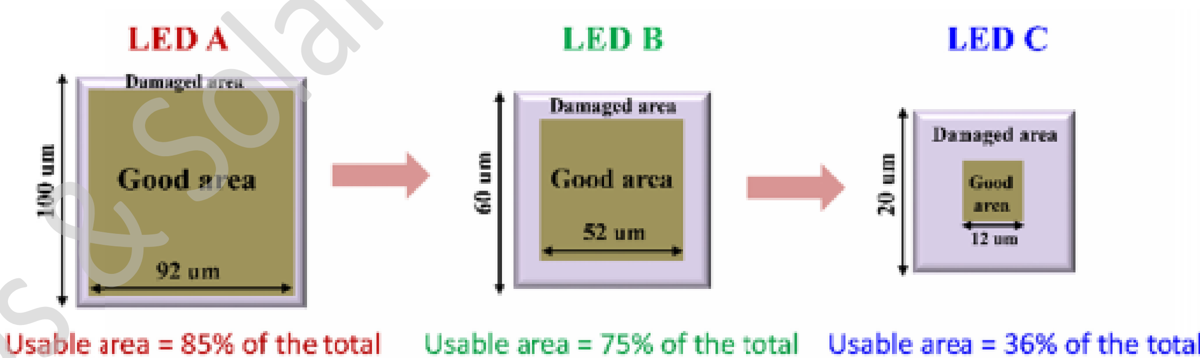

Figure 3: Scaling down LEDs enhances the surface effects due to the increase in damaged area to bulk ratio (figure from Kuo[9] et al.)

To improve the performance of micro LEDs when scaling down and reduce surface effects, surface treatment can be done. Surface treatment such as chemical etching and depositing a protective layer (passivation) can effectively improve the surface quality and increase the peak efficiency achievable[10]. At small scales, 10um, Wong[10] et al. has shown that using KOH etch and ALD treatment has improved the peak EQE from about 15% to 23%. The ideality factor of the LEDs were also improved after surface treatment, improved from 2.5 to 3.4. Below, equation 4, is the diode equation that describes the IV characteristics, where ideality factor n is included; I_s is the reverse saturation current, k is the Boltzmann constant and e is the fundamental charge. Surface damage effects the ideality and mentioned previously, improving surface treatment can restore the IV characteristics of micro LEDs to its larger counterparts.

$$I = I_s exp(eV/(nkT)) \qquad Equation\ 4$$

Simulation Results and Discussion

Simulation of LEDs and micro LEDs in this project was done through Crosslight. The LED is based in GaN/InGaN quantum wells, it is designed to emit blue at 450nm; the corresponding indium content in the quantum well is calculated with Vegards law with bowing to be 19.4%. The 2 quantum wells with 5nm active regions are separated by a undoped GaN 5nm barrier. The top p layer is a highly doped ($10^{19}cm^{-3}$) current spreading layer followed by a moderately doped($10^{17}cm^{-3}$) p layer, both 50nm thick. The bottom GaN layer is 2um thick and doped moderately ($10^{18}cm^{-3}$) for current transport to the n contact. The dimensions are all expressed in terms of L for scaling purposes, the mesa size is L while the contacts are both half length of L. A representative band diagram of a 5um LED near the active region is plotted in figure 5.

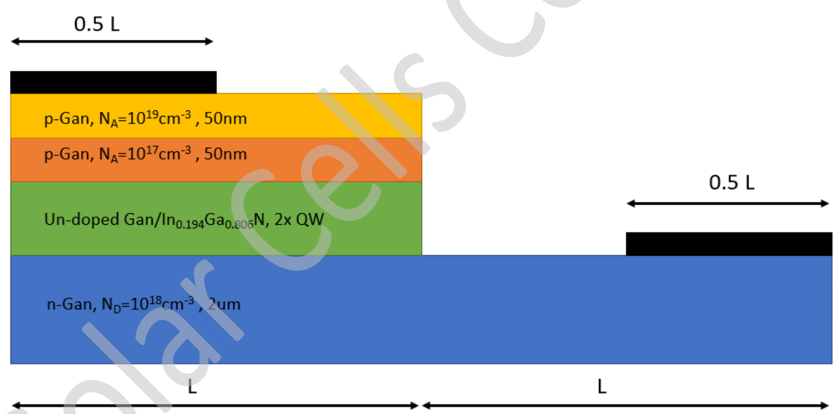

Figure 4: LED structure, dimensions in terms of L as LED is scaled down. Note, QW region total period can vary with 5nm layers

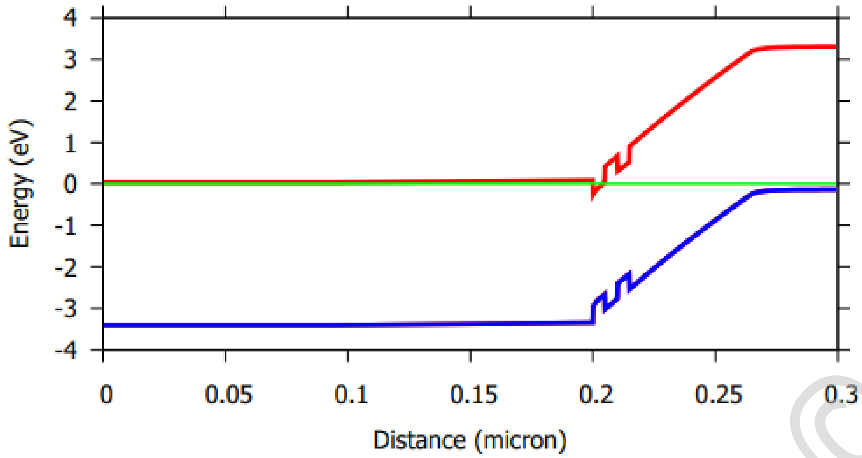

Figure 5: band Diagram of 5um LED near active region

The use in ultra high resolution displays, say 4K display that is on a mobile phone, the pitch size of each pixel is about 30um. To double to 8K we will reduce the pixel pitch by half. Current state of art III-nitride micro LED array has be fabricated at 12 micron pixel size at 15 micron pitch. Hence, in this report, we will investigate down to below 10um to gauge the behavior of these micro LEDs. For the surface properties, we will set the trap to be a mid-gap state 1.4eV below the conduction band with a density of 10^{10}cm^{-3}. The lifetimes for p and n are set to 1uS each and recombination velocity is taken that of GaN[1] and set to 5 x 10^4 cm/s; these values are for un-treated surfaces.

Scaling Effects on IQE

First set of simulation is performed with the aforementioned surface parameters, the led size L is scaled from 500um down to 2 um. There is a clear trend of reduction in overall IQE throughout the current range. At larger sizes, the IQE reduction is not as significant. Seen in figure 6, at almost all currents (some exception at lower currents), IQE is lower for LED sizes that are smaller. One interesting trend is droop is the most significant between 5 and 50 um. Droop increase in smaller sizes may be attributed to higher current densities and leakage due to thinner transport layer from the p to n contact as current does not flow as deeply into the 2um n-GaN layer. However, the reduction in droop at 2um may be due to simulation deviations when the device is too small. One trend that is not observed here is the delay of droop onset reported experimentally where peak EQE occurs at 2A/cm^2 for a 105um size and 160A/cm^2 for a 6um LED[12], the droop onset delay is attributed to better current spreading for smaller LEDs. The peak IQE for all sizes tend to be occur around 3A/m, this may be due to the design of the structure as in this report, the contacts are quite large covering half of the mesa and utilizes highly doped current spreading layer. Another possible reason is the effect of mesa size of SRH lifetime[12] , which was assumed to be constant in this report.

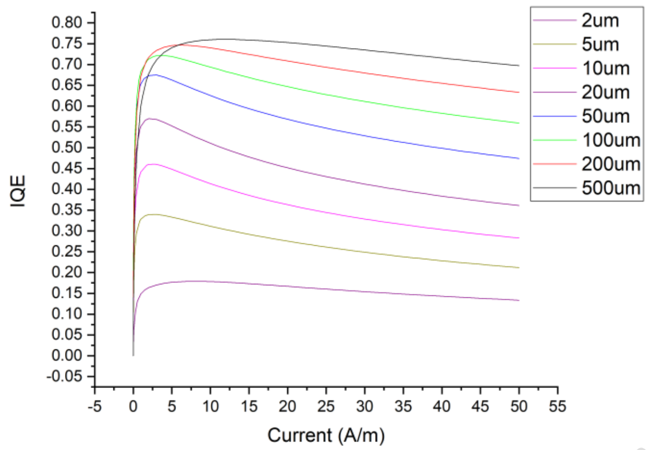

Figure 6: IQE as a function of current for different sizes

The peak IQE achieved for each size is seen in figure 7. Down until 50um, reduction is not significant only 8.6% from 74% to 67.4%. A further reduction from 50um to 20 um reduces the IQE another 10.5 % to 56.9%. The IQE reduces to a mere 17.8% at 2um. Therefore it is desired to not design mesas that are too small as there is no additional benefits to reduction of size. At 10-20 um, the IQE is 46% and 57% respectively which is still decent. Therefore, for micro-LEDs with significant surface effects it is better to make the mesa sizes only as small as necessary. This of trend of rapid decrease in IQE agrees to that of literature where mesa sizes below 50um can induce a significant reduction in IQE[13].

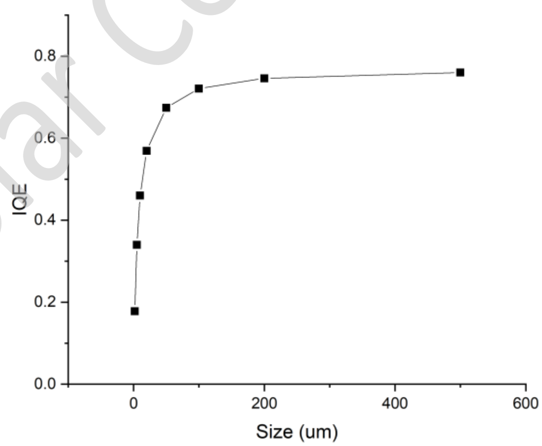

Figure 7:Peak IQE as a function of size

It is also interesting to look at the peak spontaneous emission rate of photons at 450nm. The spontaneous emission rate decreases rapidly below 50um, this behavior is similar as IQE decrease. This indicates that both surface non-radiative recombination and decrease in spontaneous emission rate contribute to the reduction in IQE as we scale the device down. To further understand the droop we can see how the different recombination rate changes as size is scaled in figure 8 (right). Here the peak recombination rates (radiative, Auger and SRH), is plotted in the structure; this is done at high operating current of 50A/m (between 3.4 and 4.1V) 0.5um away from the side walls to avoid surface effects to observe bulk behavior. The peak recombination rate occurs mostly in the first QW due to the high electron concentration there. For all 3 types of recombination, we see an increase as size is reduced. This is due to the fact that smaller LEDs have higher current densities, therefore, increasing the rate of recombination. Radiative and Auger recombination both increase significantly down to 2um, however, SRH recombination rate drops for the 2 and 5um case, this is due to SRH recombination starting to occur at a significant portion in the second QW. This effect is not seen in Auger and radiative case and the reason is not definitive. Although spontaneous emission rate decreases, the radiative recombination seems to increase, likely due to the greater increase in carrier concentration from scaling the LED down. The increased recombination rate for all three types likely contributes to droop and even when surface effects are not present(discussed in next section).

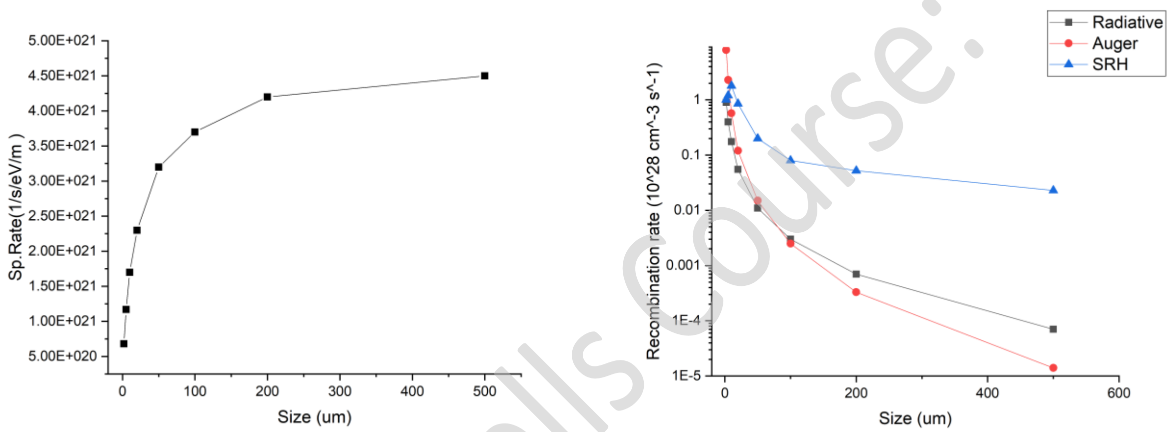

Figure 8: Size dependence of spontaneous emission rate(left), Peak Radiative, Auger and SRH recombination rate in QW bulk of the LED (right)

Scaling Without Surface Effects

With surface treatment and passivation, surface effects can be reduced and in the ideal case completely removed. Therefore, here, investigating scaling effects without the consideration of the surface effects can help us better understand and design a good micro LED. Seen in figure 8, the peak IQE achieved is not effected by the size variation, all devices are able to reach a peak IQE of 80%. The size and has a strong correlation to when the peak IQE is reached, the smaller the mesa size, the lower the current density required to reach the peak IQE, this may be due to better current spreading and transport in smaller LEDs allowing it to reach peak efficiency sooner. However, this contradicts experimental results[12] as mentioned in a previous section, however as stated before, here SRH lifetime is kept constant and surface effects are not simulated. As the LED is scaled down, it is also observed that the droop is more severe; the 500um LED only droops from 80% to about 71.3% IQE when current density is 50A/m, however the 2um LED droops much more from 80% to a mere 19.4%. This may be attributed to the increase in recombination rates for Auger and SRH in bulk seen in figure 8(right) and discussed in the previous section. If the micro LED is operated under low current, reasonable efficiency can still be achieved. For example, the worst case is the 2um LED with the most significant droop, if it was operated at below 4 A/m the efficiency remains above 50%. Therefore, if some form of surface treatment is used and peak IQE is not reduced significantly for smaller sizes, as long as the micro LED operated at a low current density, it can still have a decent IQE.

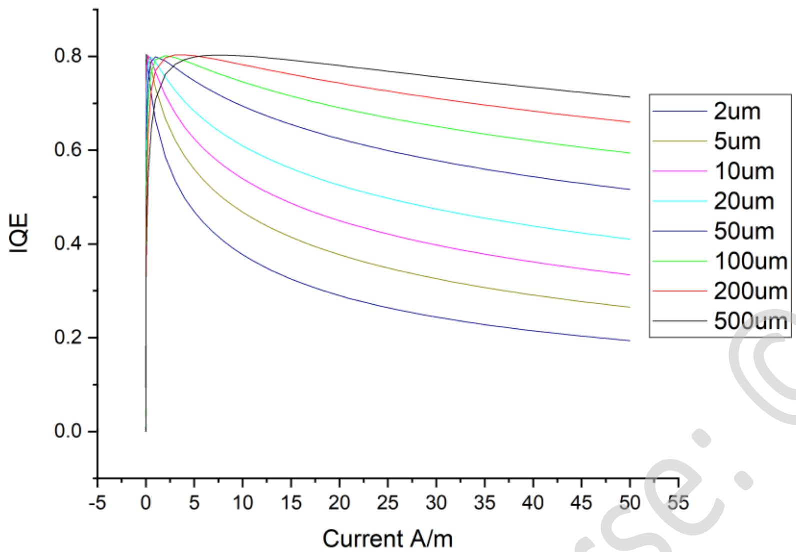

Figure 9:IQE as a function of current at different sizes

Non-radiative recombination due to surface effects

By plotting the SRH recombination in the LED we can see the effect of the surface effect's contribution to non-radiative recombination. Here we plot the SRH recombination rate in space for the 10um micro LED operated under 3.4V bias. In the case where surface effects are present (figure 10), we can see strong SRH recombination in the first QW from 0 to 0.8um in the order of 10^{28} $cm^{-3}s^{-1}$. In the case where surface effects are not present (figure 11), we can see SRH recombination from 0 to 6um, however this is in the order of 10^{25} $cm^{-3}s^{-1}$, about 1000 times less than that with surface effects; this is mainly due to intrinsic defects in the material and it occurs from 0 to 6um because that is where the current flows (below the contact from 0 to 5um). Through these special plots we can understand the significant contribution of surface defects/traps/dangling bonds to non-radiative recombination.

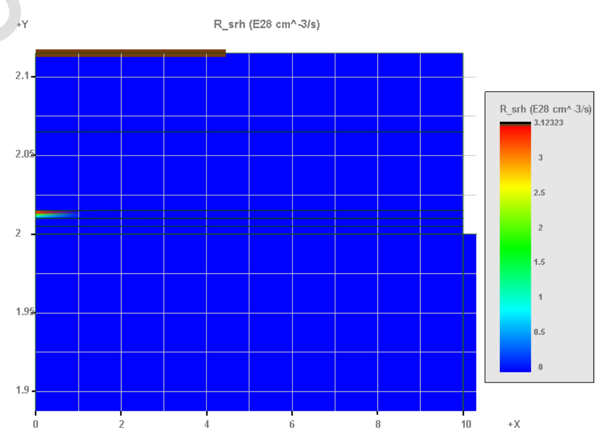

Figure 10: SRH recombination in 10um LED mesa with surface effects

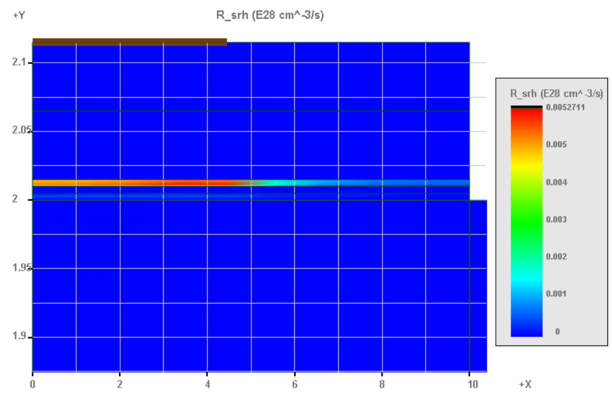

Figure 11:SRH recombination in 10um LED mesa without surface effects

Effects of MQW period

By changing the number of quantum wells, the efficiency of the LED can be improved and tuned to its desirable performance. Here, 5nm quantum well width and barrier width are used while the number of QW is varied. From figure 12, we can see that 1 QW will give the highest peak IQE at 55%, however, droop is significant when there is only one QW, this may be due to the high carrier density in the single QW aiding in non radiative recombination. When 2 QWs are used, the peak IQE is the lowest, however, droop is also the lowest at higher currents. 2 QWs has the highest IQE after about 7A/m beating out 3 QWs. 3 QWs shows the second highest IQE and has decent droop performance, barely underperforming 2QWs at currents between 7 to 50 A/m. Further increasing the quantum well number slightly degrades the peak IQE but droop remains similar to that of 2 and 3 QWs. Therefore, depending on the operating condition, 2 or 3 quantum wells is the most suitable. Below 7 A/m 3 quantum wells should be used and over 7A/m, 2 QWs should be used. However, if we are using this micro LED at a wider current range to modulate the brightness, 3 QWs should be used as it provides the highest peak IQE and is only 0.5% less efficient than 2QWs at high current.

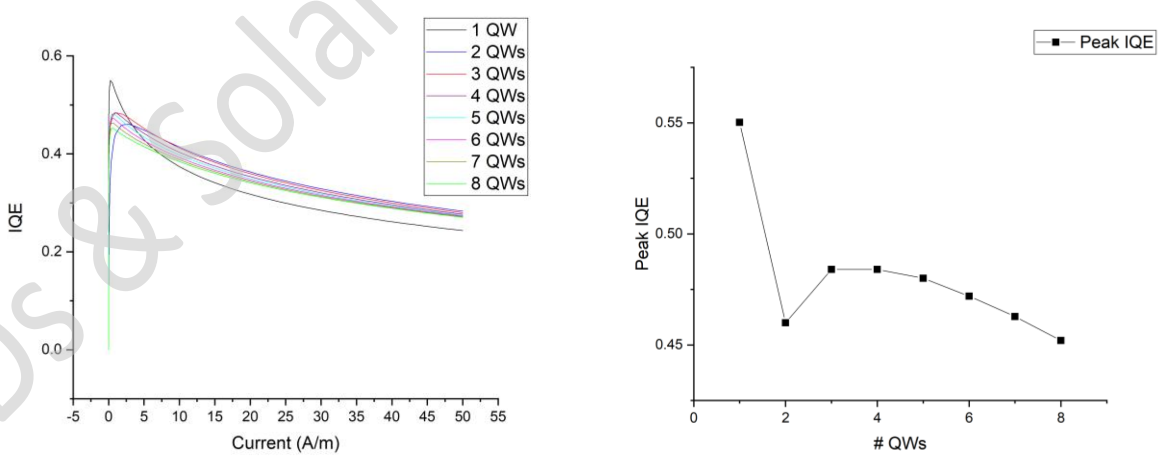

Figure 12: IQE as a function of current as # of QW is varied (left), Peak IQE as # of QW is varied (right)

Effects of MQW thickness

MQW and barrier thickness was varied between 1 and 8 nm, here 3 total period was used for all cases. There are two interesting trends which may help select a specific design, IQE as a function of current is seen in figure 13. First, peak IQE as a function of thickness starts increasing as we increase QW thickness from 1nm to 5 nm, it peaks at 48% for 5nm. Then, the peak IQE starts decreasing slightly to about 45% for 8 quantum wells, although this decrease is not significant, if operating at low currents, one may consider picking the 5 nm thick wells to operate at peak efficiency. Droop is also affected by MQW thickness, as the thickness is increased. Droop is decreased and at higher currents, above 10A/m 6-8nm quantum wells out perform the 5nm thick quantum well. There are 3 trade offs we need to consider, peak IQE, droop in IQE and cost (thicker QW is more costly to grow). For higher current operations, more thickness is better, below 10A/m, the 5nm well performs the best. The 6 or 7 nm well is a good compromise between droop and peak IQE if performance over a wide range current performance is a big factor.

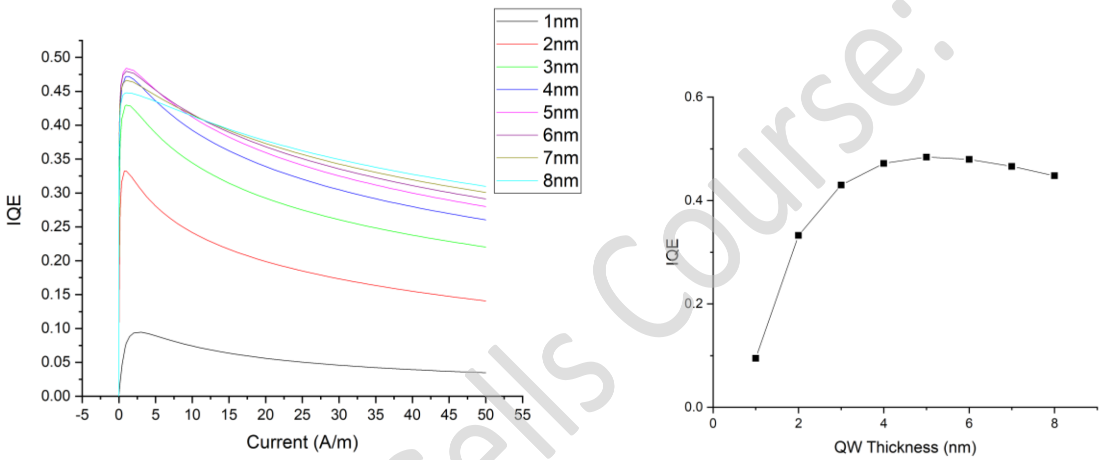

Figure 13: IQE as a function of current as QW thickness is varied (left), peak IQE as QW thickness is varied

Conclusion

With applications of display becoming more diverse and existing displays requiring higher specifications, high performance displays are needed. Conventional display technology such as OLED and LCD are reaching their limits in terms of performance and hence, next generation technology, micro LEDs are becoming a strong contender in replacing existing platforms. Micro LEDs brings in benefits from both LCD and OLED, furthermore, improves on the limits that LCD and OLED had. Smaller pixel size (hence, higher resolution), longer lifetime, higher brightness, and better color accuracy are only a few of the benefits. However, as the size of LEDs are scaled down efficiency decreases, therefore understanding and designing a micro LED suitable for display applications is important.

In this work, properties and behavior of LEDs are investigated as the size of the mesa is scaled down from 500um to 2um. Surface effects becomes increasingly important in micro LEDs because the surface area to bulk volume ratio increases as LEDs are scaled down. It is observed that efficiency begins to decrease significantly below 50um throughout the whole operation range. With surface treatment, LEDs efficiency can be improved, however, droop is still more significant for smaller LED sizes. Decrease in efficiency can be attributed to surface effects and increase in current density resulting in higher non-radiative recombination as the LED is scaled down. Therefore it benefits to use LEDs only as small as required; for ultra-high resolution sizes in the 10s of microns is enough and are still large enough to retain decent efficiency at lower currents. At 10um, effect of number of MQW periods and MQW thickness is investigated. We found that in the range of 2-3 periods and QW thickness above 5nm can result is a LED with good performance compared to others.

To improve this work, more detailed surface models and size effects can be taken into consideration for more accurate and deeper understanding of scaling effects in micro LEDs. Surface treatments that may affect surface trap level, densities and lifetimes may be modified and simulated. If possible, changing the simulation structure to include effects of a passivation layer may give further insights on how to improve micro LEDs. Size effects on carrier lifetime, carrier concentration distribution and recombination rate may also be included to improve simulation accuracy. Scaling adds another dimension to optimization of LED efficiency

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