

Improving green LEDs: A meta study into the causes and remedies of the green gap

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Abstract

This literature review investigates and evaluates different strategies to improve InGaN-based light emitting diodes (LED) by analyzing published theoretical and experimental studies. The issues of non-uniform carrier distribution, piezoelectric polarization fields and poor wave function overlap can be mitigated by the use of InGaN barriers and substrates as well as staircase designs for quantum wells (QW). It is found that QWs made for long emission wavelengths suffer from Auger recombination due to high carrier concentrations in the QWs. Lower barriers will enhance the injection of holes and thus increase the radiative recombination rate in all QWs. Piezoelectric polarization fields due to lattice mismatch can be suppressed by using InGaN barriers and substrates with decreased lattice mismatch. The radiative recombination rate is found to increase as the barriers and substrates contain higher Indium content. A large overlap design called “staggered QW” is evaluated and shown to increase wave function overlap and thus the recombination rate for InGaN LEDs. The concept of nanowire LEDs is presented as a possible solution to grow QWs with reduced quantum confined stark effect (QCSE).

Contents

1	Introduction	5
2	Theory	6
2.1	Simple LED structures	6
2.2	Modern LED internal structures	6
2.2.1	Heterostructures	7
2.2.2	Quantum well overflow	8
2.3	Lattice matching and piezoelectric fields	9
2.4	Non-radiative recombination and the ABC model	10
2.5	LED efficiency classification	11
3	Methodology	11
4	Results and discussion	12
4.1	InGaN barriers and substrate	12
4.2	Staggered QWs	17
4.3	Nanowire LEDs	18
5	Conclusion	22

1 Introduction

Modern high brightness green light emitting diodes (LEDs) are not as efficient as their blue and red counterparts [1]. This is mainly because the materials suitable for green LEDs are challenging to work with. Poor crystal quality and lattice mismatch are some of the things that scientists are working against. The poor efficiency of LEDs in the green region is sometimes referred to as “the green gap” [2]. The green gap makes it less efficient to fabricate white RGB LEDs which consists of a mix of red, green and blue LEDs. The RGB technique is a different approach to achieve white light than the common phosphorus coating of blue LEDs [3], in which blue high brightness LEDs are used to pump phosphorus which will emit yellow luminescence. The combination of blue and yellow light will then create white light. New high efficiency white LEDs used for general lighting means lower energy consumption and longer life time compared to today’s incandescent and fluorescent light bulbs [4]. A conventional incandescent light bulb uses heat radiation as light source. A filament is heated to a certain temperature at which black body radiation is emitted. Only a few percent of the intensity curve lies within the spectral region. A higher temperature of the filament would blue shift the intensity curve and thus cover more of the spectral region. Such a blue shift would require materials which do not melt at high temperatures. Tungsten with its melting point at 3695 °K is already used in most incandescent light bulbs. Contrary to incandescent light bulbs a LED does not rely upon incandescence at all. The counterpart for LEDs is called electroluminescence (EL) which means the emission of light in response to an electrical field. Light produced by a LED is almost monochromatic and there exist no such things as waste of light into the infrared region or extreme temperatures. From this point of view LEDs are far more efficient than incandescent techniques.

Both blue and green LEDs are made of InGaN which is an alloy of GaN and InN. The band gap of the alloy and thus the wavelength can be varied from 1900 nm (pure InN) down to 360 nm (pure GaN) and thus cover the whole spectral region. In theory it is possible to fabricate LEDs emitting at any visible wavelength using InGaN. In reality one can still only create efficient blue LEDs [5]. Green LEDs require more InN in the alloy in order to narrow the bandgap. The increasing amount of InN also changes the lattice constant compared to pure GaN. The inner structure of a green LED consists of several interfaces between InGaN and GaN. The different lattice constants (called lattice mismatch) lead to poor crystal quality and also strain at the interface which causes strong internal electric fields, called the QCSE. Blue LEDs require much less InN and can thus maintain higher crystal quality. The issues of large lattice mismatch and strong internal fields are not as severe for blue LEDs as they are for green LEDs. As the efficiency drops for green LEDs it will also drop for LEDs emitting at longer wavelengths such as yellow, orange and red. Such LEDs can yet only be fabricated with very poor efficiency. This thesis evaluates strategies in order to improve green LEDs and to suppress the issues mentioned above.

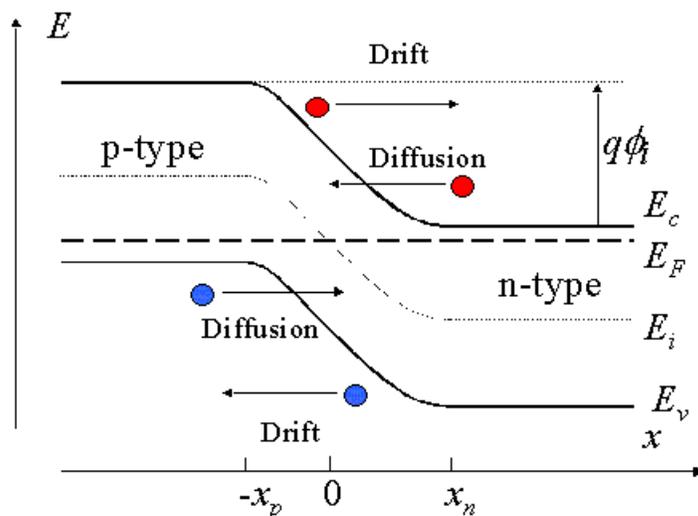


Figure 1: Pn-homojunction in thermal equilibrium [7].

2 Theory

2.1 Simple LED structures

The simplest way to understand how a light emitting diode works is to consider a p-n junction [6]. When the threshold of the forward bias is reached the electrons on the n-side will have enough energy to travel to the p-side where they will occupy vacant states in the conduction band. From there they will make a transition to the p-side valence band and recombine with a hole. This is what is called recombination of electrons and holes. The recombination process is a jump to a lower energy state and can be followed by the emission of a photon with a wavelength corresponding to the band gap (radiative recombination). There exist other kinds of recombination processes such as non-radiative recombination which is not favorable in light emitting diodes. Such recombinations often results in phonon emission and lattice vibrations which leads to heat exchange with the material.

Figure 1 shows a picture of a p-n homojunction under zero bias. The dashed line indicates the Fermi level which is constant throughout the sample. The bending of the energy bands corresponds to the potential difference between the n and p-side.

2.2 Modern LED internal structures

Modern high efficiency LEDs do not use the simple p-n homojunction for a few reasons. One of the reasons is that photons emitted in a recombination event can be reabsorbed by the material and create further electron-hole pairs. This is detrimental to device performance since fewer photons will leave the material and be used as actual light. Another reason is that when electrons are injected into the p-side they will travel an

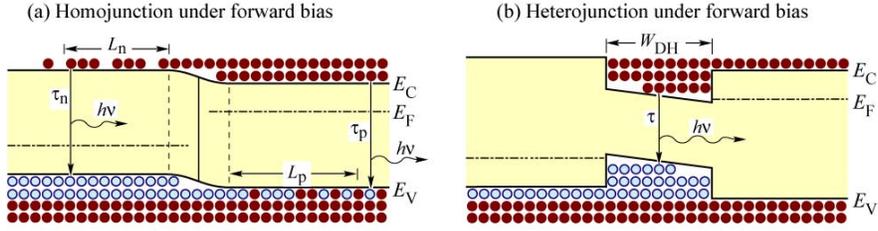


Figure 2: a) Homojunction and b) Heterostructure. [8]

average distance which is called the diffusion length L_n before they recombine with a hole. This means that carriers can diffuse far into the opposite region before recombination occurs. This gives an uneven spread of minority carriers on both sides which will affect the radiative recombination rate in a negative way.

2.2.1 Heterostructures

One approach to achieve a higher concentration of carriers is to use a heterostructure [3]. Unlike the p-n homojunction the heterostructure uses two different semiconductor materials with different band gaps. One small bandgap material is used as the active region and one large bandgap material is used as the barriers. The small band gap material is undoped and sandwiched between two pieces of doped large bandgap materials. A relevant example is InGaN as the active region with GaN barriers on the sides. The description above is actually called a double heterostructure because there are two interfaces between the small and the large bandgap materials. The point of a double heterostructure is that it works as a quantum well. Carriers that are injected into the active region (small band gap material) will be confined. They are forced into the energy bands of the active region rather than diffusing far into the opposite sides. There will thus be a large amount of carriers in the valence and conduction band of the active region which benefits the radiative recombination rate. Electrons and holes will thus recombine in the active region. The width of the active region is usually in the order of a few nanometers which, compared to the diffusion length of several micrometers, is very small. The issue of uneven distribution of carriers will thus be reduced by the use of a double heterostructure.

Figure 2 shows both a homojunction and a double heterostructure. In the heterostructure carriers are confined in the quantum well and will recombine in the small band gap material. The small bandgap material is often called “active region” because it is the place where recombination occurs. The photons emitted from the active region will have a wavelength determined by the active region band gap. The bandgap of the substrate and barrier material will thus be larger than the photon energy which reduces the probability of absorption.

Creating a double heterostructure requires two semiconductor materials with desired band gaps and matching lattice constants. This is usually the most challenging part where lattice mismatch and dislocations at the interfaces become an issue. This is

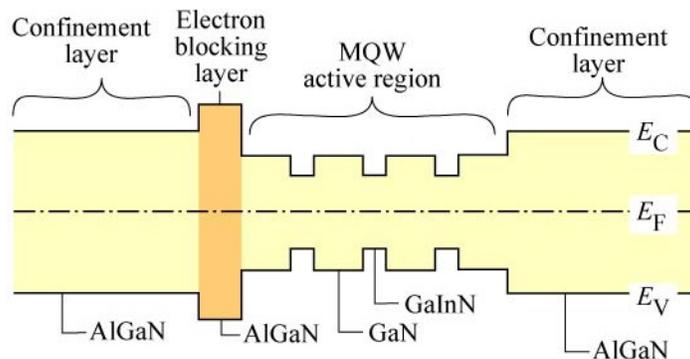


Figure 3: Electron blocking layer in a MQW structure [8].

a significant challenge when fabricating green or other long wavelength LEDs. Dislocations at the interfaces will usually result in poor efficiency and promote non-radiative recombination. Another issue is strong piezoelectric fields and the QCSE that arises from the lattice mismatch which tend to spatially separate electron and hole wave functions in the quantum well. Poor overlap of the wave functions in the quantum well leads to poor recombination rate.

Most modern LEDs consist of several double heterostructures, also called multi quantum well structures (MQW). Such structures consist of several quantum wells and intermediate barriers as shown in figure 3. The result is a larger effective active region where more carriers can be confined.

2.2.2 Quantum well overflow

A common problem with QW structures is QW overflow. A QW does not have an infinite number of available states and can thus be flooded with carriers. At high injection currents and temperatures, carrier leakage limits QW concentration and thus recombination rate. When the temperature is increased dramatically or when too many carriers are injected into the QW they start to populate energy states that are above the top of the QW. Carriers will thus no longer be confined and can escape. Carriers that escape from the QW can diffuse into the opposite sides and thus not generate light at the desired wavelength. QW overflow can be reduced by varying parameters such as barrier height, QW-width and number of QWs. Overflow of carriers mainly concerns electrons due to their higher mobility compared to holes. At the end of a MQW system it is common to use an electron blocking layer (EBL) to prevent electrons from entering the p-side. Such a layer must have a bandgap larger than the intermediate barriers in order to function as desired. Figure 3 shows a MQW structure with an EBL. An example would be InGaN QWs with GaN intermediate barriers and AlGaN as EBL which has a larger bandgap than GaN.

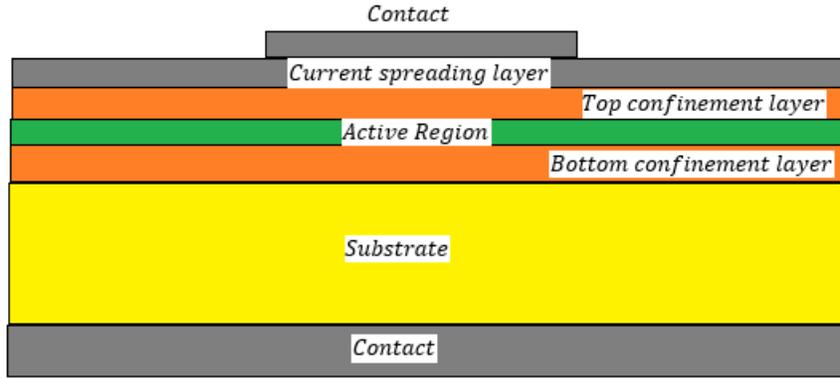


Figure 4: Different layers in a LED.

2.3 Lattice matching and piezoelectric fields

The structure of a LED consists of many interfaces between different materials. It all starts with a substrate at the bottom which serves as the ground. Other layers such as p and n-type confinement layers, active regions and EBLs are then grown onto each other using semiconductor epitaxy. The lattice constants of these materials are sometimes different which makes lattice mismatch a problem. Figure 4 shows how the different layers are grown. The result of poor lattice matching is strain between layers which can lead to piezoelectric polarization fields at the interfaces as shown in figure 5. Such fields will spatially separate electron and hole wave functions in the QW which leads to lower spontaneous recombination rates according to Fermi's golden rule [9].

$$\lambda_{if} = \frac{2\pi}{\hbar} |H'_{if}|^2 \rho(E_f) \quad (1)$$

Equation 1 gives the transition probability per unit time between the initial quantum state $|i\rangle$ and the final state $|f\rangle$. H'_{if} is the matrix element of the perturbed Hamiltonian which is responsible for the transition and $\rho(E_f)$ is the density of final states. The matrix element can be written in integral form in the following way:

$$H'_{if} = \langle \Psi_i | H'_{if} | \Psi_f \rangle = \int_{-\infty}^{\infty} \Psi_i^*(x) A(x) \Psi_f(x) dx \quad (2)$$

where $A(x)$ is the operator of the physical interaction between the two states. It can clearly be seen from equation 2 that overlap between the wave functions is necessary in order to obtain a large matrix element. Equation 1 is proportional to the square of the matrix element which means that poor wave function overlap will decrease the spontaneous recombination rate dramatically.

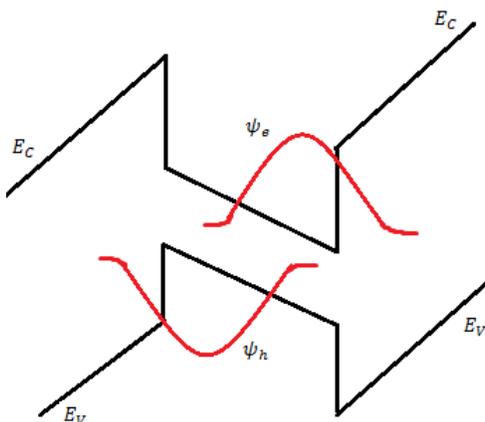


Figure 5: Spatially separated wave functions in a QW.

2.4 Non-radiative recombination and the ABC model

There are ways for electrons and holes to recombine which do not result in the emission of a photon. Such events are called non-radiative recombinations and are not desirable in LEDs for obvious reasons. One type of a non-radiative recombination event is the Auger process [23]. It involves an electron-hole pair and one additional charge carrier. In a recombination event of an electron-hole pair the excess energy is given to a third carrier which is excited to a higher state. It can either be an electron which is excited high up in the conduction band or a hole which is sent deep into the valence band. Another kind of non-radiative recombination is recombination via defects in the lattice which is followed by phonon emission. Defects can arise from the epitaxial growth of layers or as native defects in compound semiconductors. Defects that differ from the overall lattice structure can introduce new energy levels within the forbidden bandgap. These energy levels can serve as an intermediate step in a recombination event and are therefore called trap levels. Recombination via trap levels is called Shockley Read Hall (SRH) recombination.

The ABC model [10] is a model which describes the "efficiency droop" in nitride based LEDs. The efficiency droop is the phenomenon where the efficiency reaches a peak at low injection currents and then decreases with increasing injection current. The ABC model describes the internal quantum efficiency in terms of SRH recombination, radiative recombination and Auger recombination.

$$IQE(n) = \frac{Bn^2}{An + Bn^2 + Cn^3} \quad (3)$$

In equation 3 the constants A , B and C represent SRH recombination, radiative recombination and Auger recombination respectively and n is the carrier concentration. The SRH recombinations increase linearly with increasing carrier concentration whereas radiative and Auger recombination increase quadratically and cubic respectively. The

denominator in equation 3 is supposed to represent the total recombination rate. In more advanced models an extra term $f(n)$ is sometimes added to the denominator in equation 3 in order to compensate for losses such as carrier leakage from QWs [10].

2.5 LED efficiency classification

Three different classifications of LED efficiencies are most important. Those are the internal quantum efficiency (IQE), the external quantum efficiency (EQE) and the wall plug efficiency (WPE). The IQE measures the number of emitted photons from the active region per injected electron. An IQE of 100 % means that one photon is emitted for every injected electron. This is never the case in reality due to non-radiative recombination events. The IQE is defined as:

$$\text{IQE} = \frac{\text{photons emitted from active region per second}}{\text{electrons injected into LED per second}} \quad (4)$$

The IQE only considers the photons that are emitted from the active region. It does not tell whether or not they leave the semiconductor into free space. Many things can happen to photons that are created in the active region. They can be absorbed by surrounding materials such as barriers, substrates, metallic contacts or even get totally internally reflected. Many semiconductor materials have a very high refractive index which makes light extraction an issue. The angle of total reflection is usually very small which only creates a small opening for the photons. The EQE measures the amount of photons that leave the material compared to the amount of injected electrons. It is defined as the ratio of photons emitted into free space divided by the number of electrons injected into the LED per second. For obvious reason the EQE is always smaller than the IQE due to photon extraction losses.

$$\text{EQE} = \frac{\text{photons emitted into free space per second}}{\text{electrons injected into LED per second}} \quad (5)$$

The WPE is a measurement of how efficiently a LED can convert electrical power into optical power. It is defined as the ratio between the optical output power divided by the supplied electrical power. This is the efficiency the end user would measure as the LED is used in an application.

$$\text{WPE} = \frac{P_{light}}{VI} \quad (6)$$

3 Methodology

This literature review was carried out by studying some of the available scientific articles and reports on the subject. There are many ways in which LEDs can be improved which makes it necessary to narrow down the review into more specific subjects. The aim of this review is to investigate and evaluate the internal QW structure of InGaN-based

LEDs. This means the possibility to modify the QW structure in order to increase the performance and efficiency. Interesting topics for this thesis is the QCSE due to internal piezoelectric fields, the carrier injection due to the barrier height and the efficiency droop phenomenon. The listed references for this thesis were chosen such that they highlight the desired issues and possible solutions in a good presentable way. Many of the references are simulations which predicts improvements by the use of certain strategies. The simulations presented in this thesis show promising results and can thus be useful for future experimental LED prototypes with enhanced performance.

4 Results and discussion

The purpose of this thesis is to investigate the efficiency of InGaN LEDs, that is: both green and blue LEDs. Blue LEDs serve as the building block for green LEDs. A review of green LEDs is therefore also a review of blue LEDs in that manner. They both use a similar structure of InGaN/GaN MQWs. The difference is the depth of the QW and the height of the barriers. As discussed earlier we expect that blue LEDs can achieve higher efficiencies due to the less severe lattice mismatch and internal fields. On the other hand we could also expect that raising the efficiency for blue LEDs with a certain solution may also be a solution for green LEDs due to their similar structures.

There are both experimental and theoretical ways to evaluate the performance of LEDs. Pure simulations with advanced software such as APSYS from Crosslight and SiLENCE from STR Group can be used to simulate recombination rates and to investigate the band structure in LEDs. Other ways are to experimentally fabricate LED prototypes which are tested.

4.1 InGaN barriers and substrate

Conventional blue and green LEDs consist of InGaN QWs with GaN barriers. One approach to decrease the lattice mismatch at the heterostructure is to use InGaN as both QWs and barriers. InGaN as barrier material lowers the barrier height and provides better lattice match at the interface. By adding Indium to the barriers there will at some point be a trade-off between lattice matching and QW depth. More Indium in the barrier means a less deep QW which makes QW overflow more probable. The potential advantages would be weaker piezoelectric polarization fields and thus better wave function overlap in the QW which would enhance the spontaneous recombination rate. Lower barriers can also facilitate the distribution of carriers in a MQW system. Stacking of carriers in QWs can have a detrimental effect on the efficiency due to Auger recombination according to the ABC-model in equation 3 [11].

Figure 6a shows the carrier distribution in a MQW system of a conventional green $\text{In}_{0.395}\text{Ga}_{0.605}\text{N}$ LED at the injection current of 100 A/cm^2 [5]. The result from simulations performed by Yen-Kuang Kuo et al show that the carrier distribution among the QWs is non-uniform. The distribution of electrons is different from the distribu-

tion of holes. Electrons has lower effective mass and higher mobility than holes which makes it easier for them to move in response to an electric field. The electrons tend to stack up in certain QWs while the heavier holes only populate some QWs at low concentrations. The concentration of holes in the QWs decreases significantly further away from the p-side and the two QWs closest to the n-side are completely empty of holes. An explanation to this kind of non-uniform distribution could be the height of the barriers. The effect of barriers that are too high is poor injection of holes. The poor injection of holes into intermediate QWs forces the electrons to travel to the last QW near the p-side where they will be stopped by the EBL and stack up. Injected electrons that do not encounter holes in the QWs will not be able to undergo radiative recombination. The result of this is shown in figure 6b which shows the recombination events in the QWs. It shows that the only QWs that contribute to any kind of recombination events are the two QWs closest to the p-side. The Auger recombination is totally dominating over the radiative recombination events in those QWs. According to the ABC model in equation 3 the Auger recombination is proportional to the cube of the carrier concentration which can explain the issues illustrated in figure 6b.

A common issue with nitride based LEDs is the “efficiency droop” as mentioned in section 2.4. The peak efficiency is often acquired at low injection currents which is an issue for high brightness LEDs. It is desired to have the efficiency peak at high injection currents where the output power is high. LEDs that suffer from the efficiency droop are often operated in groups of several LEDs on one big chip where each LED is given a small injection current. In this way a high output power can be achieved without losing efficiency. It is a brute force solution which is inefficient in the manner that several LEDs are required. It is thus desired to shift the efficiency peak towards higher injection currents. Single LEDs at high injection currents could then produce the same output power as a chip with many LEDs at lower injection currents. A possible solution to this issue is to enhance the carrier distribution in MQW systems such that high carrier concentrations in certain QWs is suppressed. The effect would be lower carrier concentrations at certain injection currents. It would then be possible to increase the injection current and hence the output power before high carrier concentrations start to occur in the QWs. One way to suppress the Auger recombination is to enhance the carrier distribution in the MQW system such that no QWs tend to get stacked with carriers. The goal is to achieve lower carrier concentrations in the QWs and to enhance the transportation of holes. Figure 7a and b shows the same plots as in figure 6 but with $\text{In}_{0.2}\text{Ga}_{0.8}\text{N}$ barriers instead. The effect on the carrier distribution can be seen directly in figure 7a where electrons and holes are more evenly distributed than in the conventional structure. There are now holes in every QW except for last one closest to the n-side. The overall concentration of holes in the QWs has increased compared to the conventional type. The lower $\text{In}_{0.2}\text{Ga}_{0.8}\text{N}$ barriers have improved the transportation for both electrons and holes. The electron concentration in the QW closest to the p-side in 7a has decreased compared to the concentration in 6a which is beneficial for the LED performance. An explanation for this may be that the electrons do encounter holes in the intermediate QWs where they can recombine. They no longer

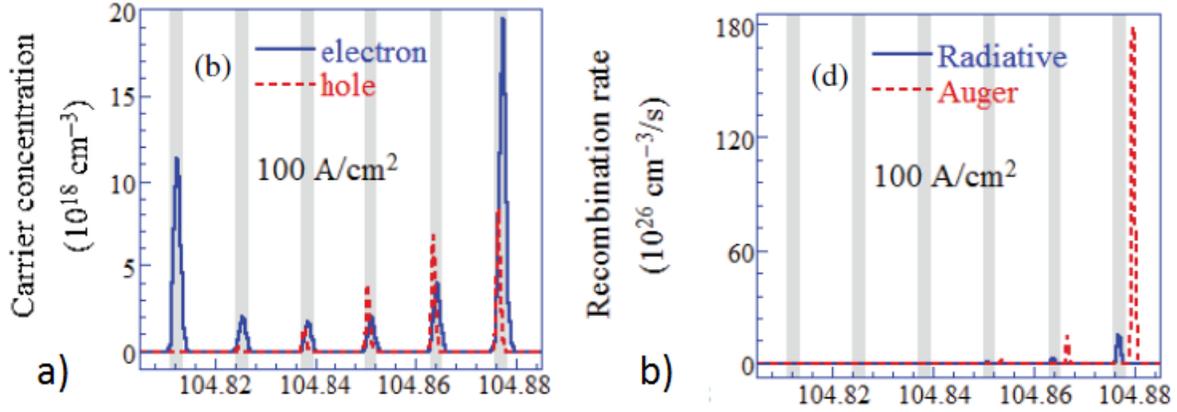


Figure 6: Carrier concentration and recombination rate density as a function of distance. The grey areas represent QWs [5].

have to travel across all the QWs to stack up near the p-side at the EBL. Figure 7b also shows how the radiative recombination rates have increased in several QWs. Auger recombination is still dominating in the QWs where the carrier concentration is significantly higher. In comparison the structure with In_{0.2}Ga_{0.8}N barrier achieves smaller carrier concentrations in the QWs than the structure with conventional GaN barriers at exactly the same current density. The low barrier structure can thus be run at higher current densities before the carrier concentration reaches similar levels as in the conventional type. This means that higher output powers can be reached before some QWs start to get flooded with electrons.

Besides from Auger recombination in QWs there are other issues such as strong polarization fields which can also be suppressed by using lower barriers or other substrates [12]. By employing lower barriers, such as switching from pure GaN to InGaN will yield better lattice match with the QWs at the heterostructure. Both the barriers and the confinement regions (conventionally GaN) can be replaced by InGaN with different Indium compositions. The radiative recombination rate is expected to increase with the use of strain balanced structures which suppress the internal polarization fields. Figure 8 shows a simulation of the electric field versus the Indium content in the QW for a green LED with In_{0.15}Ga_{0.85}N substrate and barriers [12]. The magnitude of the electric field is increasing linearly with increasing Indium content. It can also be seen that the magnitude of the electric field is always weaker for structures with In_{0.15}Ga_{0.85}N substrates and barriers than for conventional structures. Weaker polarization fields would in theory increase the wave function overlap according to equation 1 and thus the spontaneous recombination rate. Figure 9 shows the emission recombination rate versus different carrier concentration for a strain compensated structure compared to a conventional GaN structure [12]. It can be seen that the recombination rate is higher for the strain balanced structure at any carrier concentration. This clearly shows that the suppression of electric fields by the use of InGaN barriers and substrate is a promising

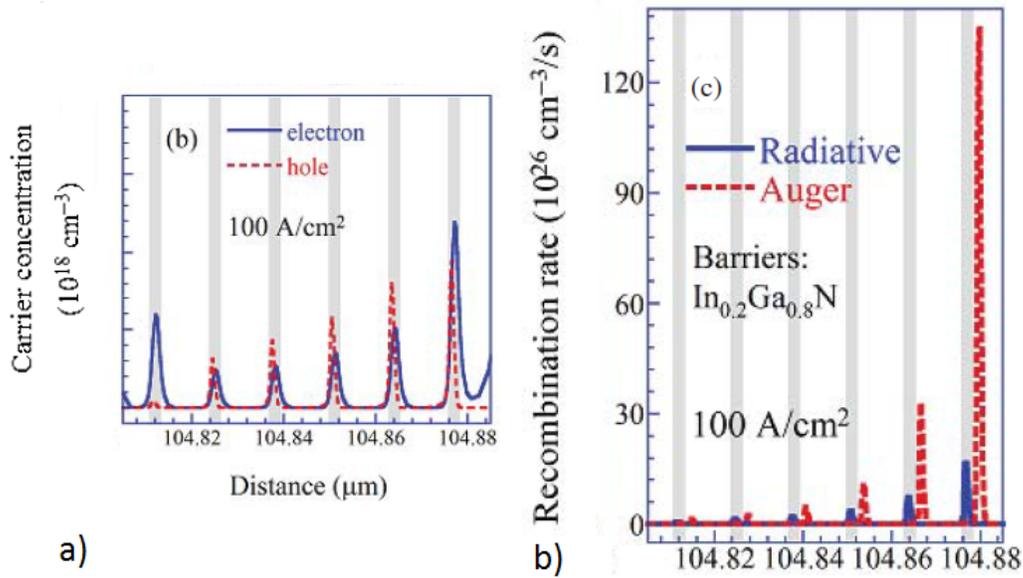


Figure 7: Carrier concentration and recombination rates in the sample with $\text{In}_{0.2}\text{Ga}_{0.8}\text{N}$ barriers [5].

strategy to improve efficiency in green LEDs.

The effect of higher emission recombination rates is higher IQE. The IQE is defined as the ratio of the emission recombination rate divided by the total recombination rate (which includes radiative, SRH recombination and Auger recombination).

As presented the emission recombination rate could be increased by employing $\text{In}_{0.15}\text{Ga}_{0.85}\text{N}$ substrates. Other results show that increasing the Indium content higher than 15% in the substrate for a fixed QW will enhance the emission recombination rate further. Figure 10 shows the emission recombination rate versus carrier concentration for QWs on different substrates [12]. The Indium content in the QW is held fixed at 30% as the Indium content in the substrate is varied between 5% and 20%. Figure 9 and 10 clearly shows that the emission recombination rate can be increased by suppression of internal fields by using substrates and barriers with better lattice match to the QWs. The use of InGaN barriers and substrates has positive effects on LED performance. It will decrease the electric fields and at the same time enhance carrier transportation by lowering the barriers. Internal electric fields and Auger recombination are two different possible explanations to the efficiency droop and low IQE nitride based LEDs. The use of InGaN barriers and substrates has shown improvements that could be of interest in high brightness LEDs in a near future. It is still hard to point out just one issue that is alone responsible for the poor performance in long-wavelength nitride LEDs.

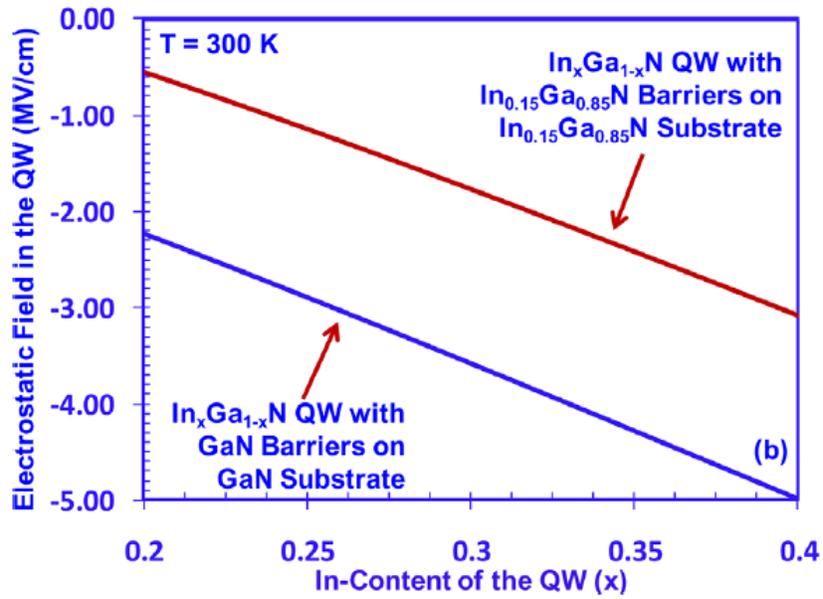


Figure 8: Electric field in QW as a function of Indium percentage [12].

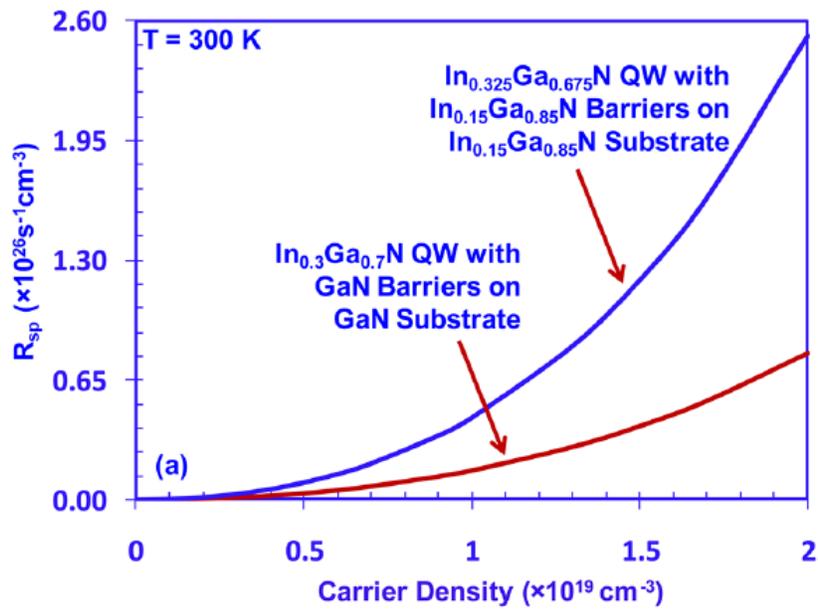


Figure 9: Spontaneous emission recombination rate density as a function of carrier density [12].

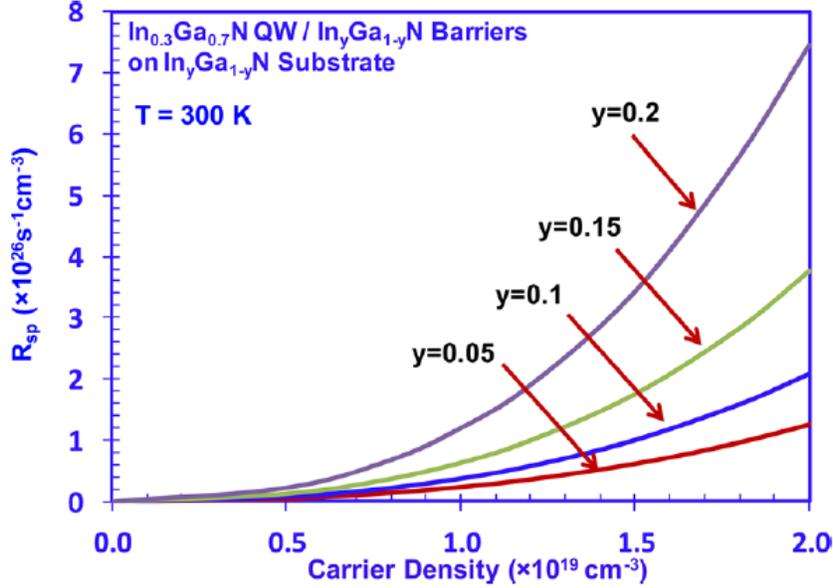


Figure 10: Spontaneous emission recombination rate density as a function of carrier density for different substrates [12].

4.2 Staggered QWs

Staggered QWs are designs that are called “large overlap designs” whose purpose is to increase the wave function overlap in MQW systems [13-18]. The design does not decrease the electric fields themselves, it rather tries to minimize the influence of such fields. An illustration of a staggered design is shown in figure 11. There are two types of common staggered designs, three-layer staggered and two-layer staggered. The design is a QW which looks like a staircase. A staggered design gets narrower further down in the QW in order to improve carrier confinement. A two-layer staggered QW has only one step in the QW whereas a three-layer structure has two steps. Figure 11 shows a two-layer staggered QW to the right where the step can be seen. $\text{In}_x\text{Ga}_{1-x}\text{N}$ serves as the actual QW and $\text{In}_y\text{Ga}_{1-y}\text{N}$ serves as the step. The Indium compositions x and y in the QW can be chosen as desired ($x > y$ for obvious reasons). The three-layer design has one additional step on the opposite side of the QW which usually has the same Indium composition as the first step.

The simplest way to confine carriers in a QW is to have a very narrow QW. This is a good way to reduce the influence of electric fields but it has other drawbacks. Narrow QWs as active regions in LEDs will suffer from small active region volume and thus be sensitive to QW overflow and blue shift in peak emission wavelength. The advantage of a staggered design is the narrow part of the QW at the bottom combined with the large volume of the QW. The staircase design in staggered QWs will force carriers to the edge of the active region conduction band where they will recombine.

The use of staggered QWs in the blue and green spectral regime has led to positive

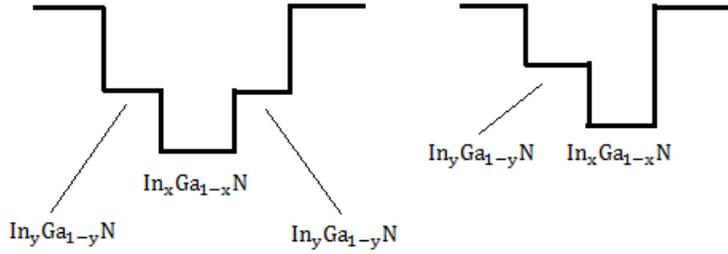


Figure 11: Three-layer staggered QW (left), two-layer staggered QW (right).

results [13-18]. Increased spontaneous recombination rate and higher output power are some of the things that comes from the increased wave function overlap in staggered QWs. Figure 12 illustrates how the wave function overlap increases in a staggered design. The narrower bottom in the QW makes carriers more confined than in conventional LEDs. Cathodoluminescence has showed that two-layer staggered QWs grown by metal organic chemical vapor deposition (MOCVD) has significantly higher output intensity than conventional designs [13]. The same staggered two-layer design as shown in figure 12 is compared to a conventional design in the intensity spectrum in figure 13. The intensity for the staggered design is approximately 3 times higher than for the conventional design. This is attributed to the increased wave function overlap. Also notice the small blue shift of 10 nm in peak emission wavelength for the staggered design.

It is common that staggered designs experiences a small blue shift in peak emission wavelength. The reason is that the narrower bottom of the QW gets filled with carriers quicker than other conventional designs, also known as the state filling effect. The recombination events will then occur from states that are further away from the edge of the conduction or valence band. The blue shift is not an issue itself; it is rather the band filling that can possibly saturate the efficiency at high carrier concentrations. If the bottom part of the QWs in figure 11 would get filled due to band filling, then the confinement of carriers could be lost. Carriers that are located above the step in a staggered design will not be confined as desired. The large wave function overlap would not apply in such situations. A heavy blue shift in staggered QWs can thus indicate that some of the carrier confinement has been lost. There can thus be a trade-off between wave function overlap and carrier concentration. Conventional designs do also experience some blue shift due to band filling at high carrier concentrations. It is usually not as severe as for staggered designs which sometimes need slightly higher Indium content in the QW to compensate for the blue shift compared to conventional types.

4.3 Nanowire LEDs

A new approach to fabricate high performance LEDs is to use nanowires. A nanowire is a thin wire where the diameter and length is in the order of tens and hundreds

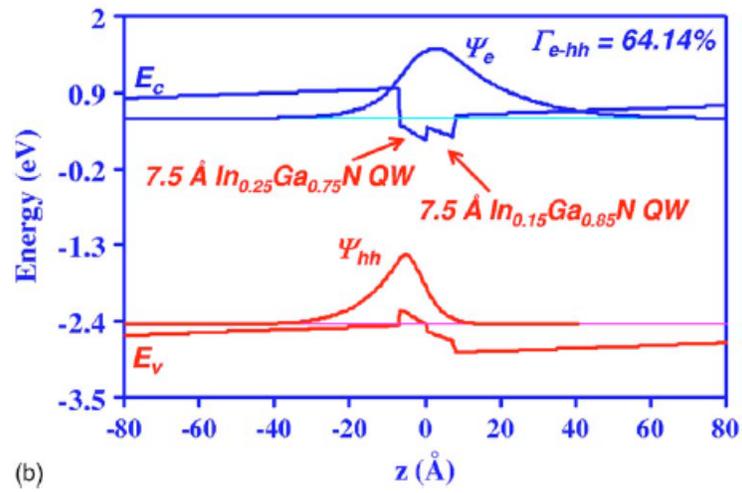
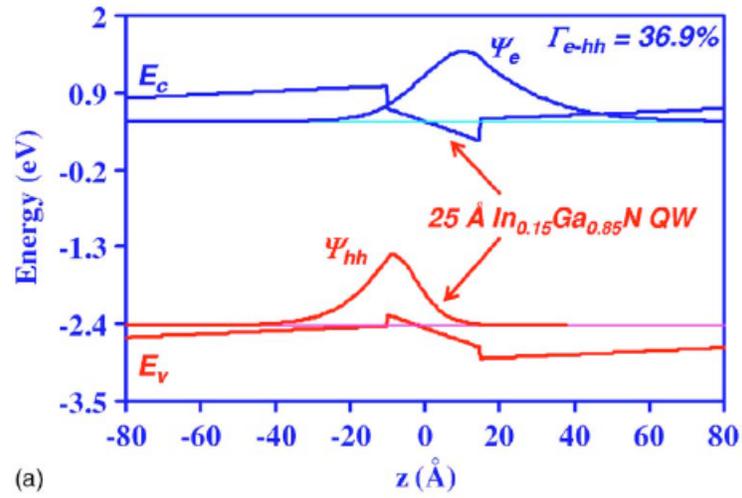


Figure 12: Band line up for a two-layer staggered QW [17].

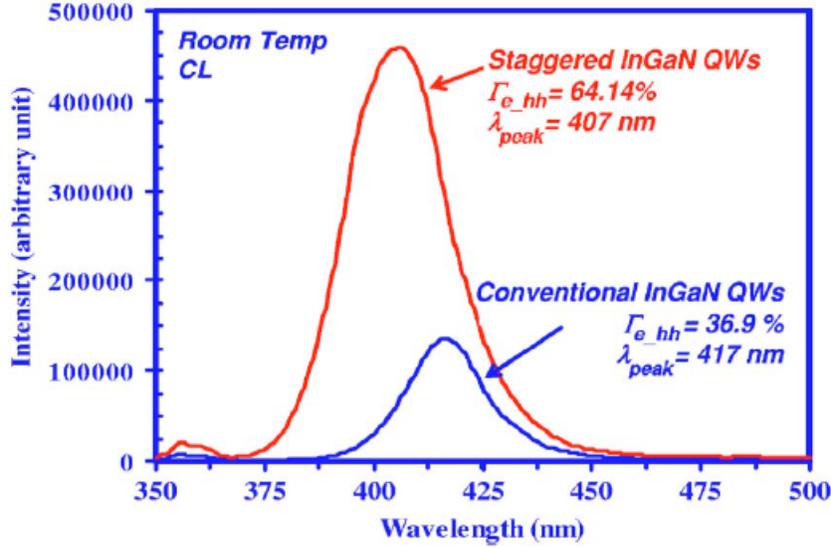


Figure 13: Intensity spectrum for a staggered two-layer design compared to a conventional design [13].

nm respectively. There are two types of nanowire LEDs that are of interest, the axial wire and the radial wire. In an axial nanowire the heterostructures are grown axially throughout the wire whereas they are grown radially in a radial nanowire. Both kind of wires are illustrated in figure 14 where they are grown on a mask. The thick layer in figure 14 represents a GaN layer on which the mask is grown. The mask is an insulating material such as silicon nitride and is filled with small opening where the nanowires are grown. The purpose of the mask is to separate parts of the nanowires from the GaN layer. Notice that the structures shown in figure 1 are grown onto large substrates such as silicon or sapphire wafers which are not shown in figure 14.

One advantage of nanowire LEDs compared to planar LEDs is the low material consumption. The standing nature of the nanowires as illustrated in figure 14 allows many nanowires to be grown onto large and less expensive substrates. Another advantage compared to planar LEDs is the improved light extraction efficiency due to the geometrical shape. Radial nanowires offers a special advantage which is growth of the QWs along the m -axis which is illustrated by the arrows in figure 15. The nanowires are grown straight up in the c -direction of GaN. The radial shells which forms the heterostructures makes the QWs grow along the m -axis. The m -axis is a non-polar direction which is free from piezoelectric fields which means that the QCSE will not be an issue as the Indium content in the QWs is increased. The result of this is the the possibility to fabricate long-wavelength LEDs with high Indium content QWs with good wave function overlap. Companies such as Glo and Aledia are currently conducting research in this field [19, 20].

Figure 15 illustrates a single radial nanowire grown on GaN. The thin layer between the nanowire and the GaN layer is the mask. The mask allows only the core of the

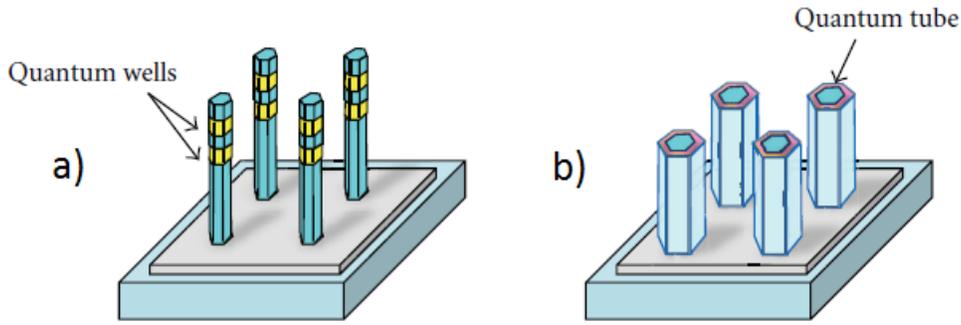


Figure 14: a) Axial nanowire LED , b) Radial nanowire LED.

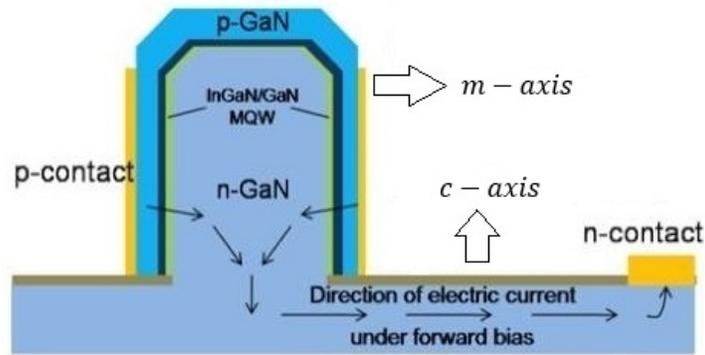


Figure 15: Radial nanowire on c-plane GaN with QWs along the m-axis.

nanowire to have direct contact with the GaN layer. This is important when current is flowing through the wire. The core is n-doped GaN on which the QWs are grown radially in shells. After the QWs comes the p-doped GaN layer which is followed by the outermost p-contact layer, a transparent conductive oxide film (TCO). The purpose of the TCO is to spread current into the nanowires from all directions as shown in figure 15. The current will then pass radially through all the layers and into the core. The core as mentioned earlier has direct contact with the GaN layer which makes the current flow as illustrated in figure 15. The mask isolates all the layers except the core from the GaN layer which prevents unwanted current leakage.

A real nanowire LED chip fabricated by Glo is shown in figure 16. The zoomed in part shows how the nanowires are grown. The two circular objects are the contacts, the cathode is connected to the GaN layer and the anode is connected to the TCO which covers all of the nanowires. An important property of the TCO is the transparency to visible light. Light that is created in the nanowires must be able to enter free space

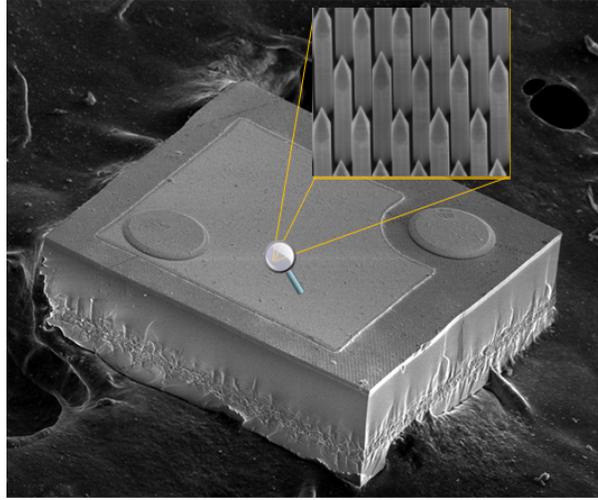


Figure 16: Nanowire LEDs on GaN substrate [19].

without being absorbed.

5 Conclusion

The strategies evaluated in this thesis show positive results on the performance of InGaN LEDs in the blue and green spectral regime. The strategy of employing lower InGaN barriers is a way to evaluate if the poor performance and the efficiency droop is caused by non-uniform carrier distribution and strong electric fields. Even though positive results are acquired it is hard to pinpoint a certain effect as the issue. It is believed that a combination of effects are responsible for the poor performance of long-wavelength LEDs. Some of these issues include Auger recombination, polarization fields and poor crystal quality (SRH recombination). It was shown that lower barriers contribute to a more uniform carrier distribution as in figure 7 which is beneficial. Some of the intermediate QWs benefit from better carrier distribution as shown in the plot of recombination rates in figure 7. On the other hand there is still significant Auger recombination the QWs closest to the p-side which is detrimental for emission efficiency. Lower barriers may prove a potential solution if the injection of holes is poor, which is usually the case for deep QWs. The electrons will also increase their transportation ability between QWs when the barriers are lowered. This could be what causes the large Auger recombination rates in the last QWs near the p-side. Electrons with their lower effective mass are allowed to move too easily and thus stack up in certain QWs. A big issue seems to be that electrons and holes have different effective masses which makes it counterproductive to lower the barrier height. It would be good if the barrier height could be modified to fit both electrons and holes such that no stacking of electrons or poor injection of holes occurs. It is possible that modification of the barriers in other ways will lead to better results than the results presented here. At the end it

will probably come down to a trade-off between hole-injection and electron stacking. The best case scenario would be to have different barriers for electrons and holes such that the height could be varied separately in the valence and conduction band. This solution could maybe be possible by some kind of doping of the barriers in the MQW structure. Impurities with energy levels in the bandgap above the valence band maybe would help the transportation of holes. The new energy levels would lower the valence barriers while the conduction band barriers would be unchanged.

The suppression of electric fields by new barriers and substrates has shown to be useful as in figure 8 and 9. Emission recombination rates seem to increase in response to the suppressed electric fields and increased wave function overlap, however there are many theories of what goes on when the barriers are lowered in a MQW system. By this reason it is very difficult to tell which effect that is responsible for the experienced improvement. Simulations show that both carrier distribution and suppression of electric fields benefit from new barrier designs which makes such designs interesting for new high performance LEDs [5, 12, 13]. A combination of lower barriers and staggered QWs could be an efficient solution for both planar and nanowire LEDs. The strategies of lower barriers and staggered QW designs apply in theory to all LEDs that employ heterostructures. The design of the LEDs, nanowire or planar, is of no importance for the validity of the strategies discussed here.

There are many ways in which InGaN LEDs can be improved. This thesis has mainly focused on the internal strategies concerning the QWs and the internal efficiency. There are other issues that can drain LED performance such as the extraction efficiency and the EQE which needs to be improved further [21, 22].

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