III-nitride optoelectronic devices containing wide quantum wells—unexpectedly efficient light sources

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In this paper we review the recent studies on wide InGaN quantum wells (QWs). InGaN QWs are known to suffer from an extremely high built-in piezoelectric polarization, which separates the electron and hole wavefunctions and causes the quantum-confined Stark effect. We show both by means of modeling and experimentally, that wide InGaN QWs can have quantum efficiency superior to commonly used thin QWs. The high efficiency is explained by initial screening of the piezoelectric field and subsequent emergence of optical transitions involving the excited states of electrons and holes, which have a high oscillator strength. A high pressure spectroscopy and photocurrent measurements are used to verify the mechanism of recombination through excited states. Furthermore, the influence of QW width on the properties of optoelectronic devices is studied. In particular, it is shown how the optical gain forms in laser diodes with wide InGaN QWs. © 2021 The Author(s). Published on behalf of The Japan Society of Applied Physics by IOP Publishing Ltd

1. Introduction

The heterostructures based on the III-nitride material system have extremely high built-in spontaneous and piezoelectric fields due to the broken inversion symmetry in the uniaxial crystal structure.1–3 The growing understanding of the nature of these fields allowed to use them for unique physical phenomena such as doping-free high electron mobility transistors4–8 polarization-induced doping9 or enhancement in the tunneling current.10–12 However, there are also applications of III-nitrides in which the built-in electric fields are detrimental. The optoelectronic devices with InGaN quantum wells (QWs) are one example. The electron and hole wavefunctions inside the InGaN QW are spatially separated,13–22 which leads to a decrease of the oscillator strength. The low probability of recombination leads to a high carrier concentration. This is unwanted because as the carrier density increases a growing part of the carriers recombine through the nonradiative Auger process, causing the reduction of the quantum efficiency.23–27 Additionally, the polarization field increases with composition of the InGaN QW causing a higher separation of carrier wavefunctions. This has been found to be the primary reason for the loss of efficiency of the III-nitride devices in the green spectral range.28,29 The issue of loss of efficiency in the green spectral region is of great importance, because there is no other semiconductor family, which can be used to construct devices emitting green light.

The LEDs based on InGaN are used in an increasing number of applications. However, the biggest one is the general lighting.28 In fact, the III-nitride material family has revolutionized this market in the past two decades. General lighting is responsible for 15% of global electricity consumption.30 The US Department of Energy forecasts that the savings in energy consumption by 2030, thanks to use of III-nitride LED, will be roughly 260 TWh annually.31 This will reduce the consumption of fossil fuels and generation of air pollution and greenhouse gases and help to create a sustainable society. These enormous savings come from the exceptionally high efficiency of InGaN LEDs in violet and blue colors.32 Any increase in the efficiency of InGaN will reduce the electricity consumption for general lighting even further. However, the biggest advantage might come from the improvement of efficiency of green LEDs. Today, the white light, emitted by LEDs, is generated by mixing the violet (or blue) light from InGaN and yellow light from phosphorous, which is excited by the light originating from InGaN.33 The conversion from violet (or blue) light to yellow is associated with a loss in energy even if the quantum efficiency of emission from phosphorous would be equal to 100%. A different kind of approach is mixing of blue, green and red colors, which would be emitted directly from the semiconductor material. Today, the quantum efficiency of green emitters is the bottleneck to realization of this approach. If the efficiency of green emitters could be improved—it would result in reduction of the electricity consumption on the global scale.

The physical mechanism hindering the efficiency of emitters in the green spectral region is the low oscillator strength of high indium content InGaN QWs caused by strong separation of electron and hole wavefunctions.30 This leads to a high accumulation of the injected carriers in the QW, which induces an increase in the probability of recombination through the non-radiative Auger processes. Several methods of increasing the oscillator strength in InGaN QWs had been proposed. The two main ideas rely on reduction of built-in polarization through either a growth of staggered QWs34,35 or growth on semipolar and nonpolar crystal orientations.36–41 Ideally, the solution to reduce the carrier density would be to increase the volume of the active region by increasing the thickness of the QW. However, due to the polarization-induced separation of carrier wavefunctions, it was shown that the transition...
probability decreases severely for wide InGaN QWs.\textsuperscript{14,42} However, among many reports in the literature showing the experimental data on thick InGaN QWs,\textsuperscript{17,42–46} some of them document an increase in the efficiency.\textsuperscript{44,45} Additionally, the current state-of-the-art violet laser diodes (LDs) incorporate wide (6.6 nm thick) InGaN QWs.\textsuperscript{47} Moreover, in a very recent, first demonstration of deep-ultraviolet LD, the active region is composed of a 9 nm thick AlGaN QW.\textsuperscript{48} There clearly is a lack of understanding of the origin of efficiency of wide InGaN QWs.

In this paper we will discuss the recent advancement in the comprehension of the physics of optical transitions in wide InGaN QWs. We have shown that there exists a surprisingly efficient recombination channel in wide InGaN QWs.\textsuperscript{49} This is counterintuitive, because the wide InGaN QWs are expected to have a low wavefunction overlap due to severe separation of electrons and holes.\textsuperscript{14,42} However, the high oscillator strength in these heterostructures comes from transition involving excited states. The distribution of carriers on $e_2$ and $h_2$ states along the whole QW thickness ensures the low carrier density and reduced recombination through the Auger process.

The paper is divided into several sections. In Sect. 1 the introduction and motivation of the conducted studies has been given. In Sect. 2 we shall discuss the results of theoretical simulations that predict a high wavefunction overlap between excited states in wide InGaN QWs.\textsuperscript{49} Additionally, we will show that, surprisingly, a higher increase in the wavefunction overlap is achieved in QWs emitting in the green spectral region. Finally, we will consider the impact of QW thickness and wavefunction overlap on the internal quantum efficiency (IQE). In Sect. 3 we will review the experimental evidence for the emission from excited states in wide InGaN QWs and show that these transitions can have a higher efficiency than the transition between ground states in thin QWs.\textsuperscript{49} We will also discuss the recent experiments of photo-induced current showing that there exist built-in electric field in wide InGaN QWs prior to excitation.\textsuperscript{50} Additionally, we will show by means high pressure measurements that the field in a wide QW is screened as soon as current is supplied.\textsuperscript{51} In Sect. 4 we will present the application of the wide InGaN QWs to LDs.\textsuperscript{52} We will study the influence of QW width on formation of optical gain in blue and cyan LDs. Additionally, we will discuss the differences in lasing spectrum between LDs with thin and wide InGaN QWs.

2. High oscillator strength in wide InGaN QWs

2.1. Mechanism of emergence of optical transitions through excited states

In this section we will discuss results of simulations of wide InGaN QWs, which show that there exist efficient recombination paths involving excited states. However, as we will show, this efficient transitions appear only after external excitation, either optical or electrical.

In order to calculate the band profile of the QWs without and under excitation we used the SiLENSe 5.4 package,\textsuperscript{53} which uses the drift-diffusion model and solves the Schrödinger equation to obtain the distributions of wavefunctions and their overlaps. Structure used in simulations is presented in Fig. 1(a). It consists of an InGaN QW embedded in GaN quantum barriers (QB) and is placed in a pn diode in

![Fig. 1.](Color online) (a) Schematic structure used for the simulations. Calculated band profiles and wavefunction distributions of the active region composed of a thin and wide QWs for a current density of: (b) 0 A cm$^{-2}$ and (c) 100 A cm$^{-2}$. Only the active region, depicted in (a), is presented for clarity. Reprinted with permission from Ref. 52. Copyright (2019) The Japan Society of Applied Physics. Values of selected wavefunction overlaps are given. (d) Dependence of wavefunction overlap on current density for thin and wide QWs. Reprinted with permission from Ref. 49. Copyright (2019) American Chemical Society.
order to simulate electrical injection. A standard AlGaN electron blocking layer is placed on the p-type side to prevent electron overflow.

Here, we will discuss two QWs with widths of 2.6 and 10.4 nm, which we will refer to as a thin and a wide QW, respectively. Figures 1(b) and 1(c) present the calculated band structure of both QWs without and under current injection, respectively. The piezoelectric polarization causes a spatial separation of the electron and hole wavefunctions. In case of the thin QW, the wavefunction overlap between the ground states is 0.19 at zero current. Under current injection the piezoelectric charges are partially screened by carriers and the resultant electric fields is lower than in the case without excitation. Therefore, the wavefunction overlap is higher under excitation and at $j = 100$ A cm$^{-2}$ the $\langle e1h1 \rangle$ is equal to 0.39.

Prior to current flow, the piezoelectric field has the same magnitude in both QWs, which results in a very large spatial separation of the ground states in the wide QW, as can be seen in Fig. 1(b). The $\langle e1h1 \rangle$ wavefunction overlap is extremely low, on the order of $1 \times 10^{-11}$. Under excitation the bandstructure of the wide QW changes immensely [see Fig. 1(c)]. The band profile is almost flat in the middle of the QW. Electric field is still present at the edges of the QW, due to the fact that the piezoelectric charges are two-dimensional and are located at the interface, while mobile charge carriers are partially spread in the $\hat{c}$ direction. The ground states are still localized in these remnants of the piezoelectric field. Therefore, even after the field is screened the overlap is still extremely low and is equal to $6 \times 10^{-4}$ at $j = 100$ A cm$^{-2}$. This is consistent with earlier works by Della Sala et al.\(^{43}\) and Young et al.\(^{42}\) who have shown that even at high injection the wavefunction overlap between the ground states is negligible.

The reason why the band structure of the wide QW at $j = 100$ A cm$^{-2}$ is so different than the thin QW is due to interplay of carrier injection and recombination. In the case of a wide QW, the injected carriers do not initially recombine because of nearly zero wavefunction overlap. Instead, the number of carriers will grow until a recombination path appears. Eventually, the piezoelectric field gets almost entirely screened and the excited states start to change their spatial distribution. Prior to excitation the excited states were localized at the edges of the QW, similarly to the ground states as can be seen in Fig. 1(b). However, as soon as piezoelectric field gets screened the excited states distribute along the whole length of the QW as can be observed in Fig. 1(c). This happens because the confinement energy of the excited states is higher than that of the ground states and they are not localized in the remnants of the piezoelectric field at the edges of the QW.

Thanks to the fact that the excited states are localized across the whole length of the QW their overlap is exceptionally high. For instance, the $\langle e2h2 \rangle$ transition has a very high wavefunction overlap of 0.56 at $j = 100$ A cm$^{-2}$. Therefore, a steady state arises in which the subsequently incoming carriers recombine through the excited states and the carrier density in the QW stabilizes. It is important to stress that, unexpectedly, the $\langle e2h2 \rangle$ wavefunction overlap is higher than the overlap between ground states in a thin QW.

The full evolution of the wavefunction overlap for selected transitions is presented in Fig. 1(d). Interestingly, the transitions involving quantum states with even and odd numbers are not forbidden as in the case of a rectangular QW. Transitions such as $\langle e2h1 \rangle$ and $\langle e1h2 \rangle$ are allowed and can have high wavefunction overlap due to symmetry breaking by the built-in electric field. In the case of a 2.6 nm QW the wavefunction overlap of the $\langle e1h1 \rangle$ transition increases with current density due to partial screening of the piezoelectric field by carriers. In the case of a 10.4 nm QW the ground state transition is becoming nonnegligible only at very extreme current densities. Interestingly, there is a very high wavefunction overlap for the $\langle e2h2 \rangle$ even at very low current densities. This should not be surprising, because as discussed earlier, the supplied carriers do not recombine before a sufficient number, which screens the piezoelectric field, is reached. In this view, it is actually necessary for one of the transitions to have a nonnegligible overlap in order to stop the increase in the carrier number.

It is interesting to observe how the transition from the thin to a wide QW occurs. Figure 2 presents the calculated dependence of wavefunction overlaps on QW width for the two lowest electron and hole states. The dash–dot line was calculated for QWs without carrier injection, while the solid lines represent a situation of high current density of $j = 2000$ A cm$^{-2}$. The green shaded area depicts the width of the QW commonly used in LEDs and LDs. The wavefunction overlap between the ground states drops significantly with the increase of the QW width as expected due to the increase of their spatial separation by the built-in electric field. Interestingly, the $e2$ state starts to be confined inside the QW only for widths above 4.1 nm. As soon as the $e2$ state appears it has an unexpectedly high wavefunction overlap with the $h1$ state. Surprisingly, the $\langle e2h2 \rangle$ transition has a nearly zero wavefunction overlap for widths below 5 nm. The behavior of $\langle e2h1 \rangle$ and $\langle e2h2 \rangle$ clearly show the complexity in the distribution of the wavefunctions in an InGaN QW with fixed charges at the edges and mobile carriers inside the QW. For QW width above 5 nm the wavefunction overlap of the $\langle e2h2 \rangle$ transition starts to increase and above 11 nm is the highest. At the same time the mixed $\langle e2h1 \rangle$ and $\langle e1h2 \rangle$ transitions start to decrease. This is because together with the increase of QW width the influence of the edges of the QW

Fig. 2. (Color online) Dependence of wavefunction overlap on thickness of the QW. The dash–dot and solid lines are calculated for a current density of $j = 0$ and 2000 A cm$^{-2}$, respectively. The green shaded area depicts the commonly used InGaN QW thicknesses. Reprinted with permission from Ref. 49. Copyright (2019) American Chemical Society.
direction we estimated the mobile carrier current density was set to Fig. 3. (Color online) Dependence of wavefunction overlap on In
ground states drops with the composition. The decrease of the
for a high InGaN composition. This is extremely important
We will now discuss a peculiar feature of the wide QWs. We
2.2. Mitigation of the green gap problem with wide
InGaN QWs
We will now discuss a peculiar feature of the wide QWs. We noticed that an exceptionally high wavefunction overlap between the excited states in wide QWs can be obtained for a high InGaN composition. This is extremely important due to the fact, that the wavefunction overlap between the ground states drops with the composition. The decrease of the wavefunction overlap of the \( \langle e1h1 \rangle \) transition was proposed as the major factor which causes the drop of quantum efficiency of in the long wavelength LEDs based on InGaN QWs.\(^ {29}\)
Here, we will compare the influence of InGaN composition in a thin (2.6 nm) and a wide (10.4 nm) QW. We have simulated the band structures and wavefunction distributions for In\(_{x}\)Ga\(_{1-x}\)N QWs with composition \( x \) changed in a wide range from 0.12 up to 0.37. The calculated dependence of wavefunction overlaps on composition at a high injection current of \( j = 2000 \ \text{A cm}^{-2} \) for several transitions are presented in Figs. 3(a) and 3(b) for a thin and a wide QW, respectively. In the case of a 2.6 nm QW the \( \langle e1h1 \rangle \) transition is very high in the low QW composition range. However, as the composition increases the magnitude of the piezoelectric charges at the QW interfaces increases. This causes a stronger built-in electric field and a greater separation of the electron and hole wavefunction. Therefore, the wavefunction overlap of the \( \langle e1h1 \rangle \) transition drops and at a composition of \( x = 0.30 \) is equal to 0.35. The band profile of a 2.6 nm In\(_{0.3}\)Ga\(_{0.7}\)N QW is presented as an inset to Fig. 3(a). The piezoelectric field is much stronger than in the In\(_{0.17}\)Ga\(_{0.83}\)N QW presented in Fig. 1(c).
In the case of a wide QW, the transition between the ground states becomes less probable as the composition is increased. Instead, the \( \langle e2h2 \rangle \) transition has the highest wavefunction overlap above a composition of \( x = 0.18 \). It is interesting to see that the \( \langle e2h2 \rangle \) transition reaches a maximum overlap of 0.65 at a composition of \( x = 0.30 \), above which it starts to slightly drop. It is striking that in the case of In\(_{0.3}\)Ga\(_{0.7}\)N, commonly used in green LEDs, the wavefunction overlap between excited states in a wide QW can be almost twice as high as in the thin QW. It is important to note that in the case of In\(_{0.17}\)Ga\(_{0.83}\)N QW, discussed earlier, this difference was not so extensive. The reason for the larger difference in the case of the higher InGaN composition lays in the higher strength of the piezoelectric polarization of In\(_{0.3}\)Ga\(_{0.7}\)N QW. On one hand, in the case of the thin QW the higher built-in polarization causes a lower \( \langle e1h1 \rangle \) wavefunction overlap for the In\(_{0.3}\)Ga\(_{0.7}\)N QW. However, after screening of the piezoelectric polarization the shape of the QW with higher In content resembles a rectangular shape more and therefore the \( \langle e2h2 \rangle \) transition has a higher overlap than in the case of In\(_{0.17}\)Ga\(_{0.83}\)N QW.

\[ \text{Fig. 3. (Color online) Dependence of wavefunction overlap on In}_{x}\text{Ga}_{1-x}\text{N QW composition for: (a) a thin 2.6 nm QW and (b) a wide 10.4 nm QW. The current density was set to } j = 2000 \ \text{A cm}^{-2} \text{. Inset to (a) presents the calculated band profile of an In}_{0.3}\text{Ga}_{0.7}\text{N QW together with the confined quantum states. Reprinted with permission from Ref. 49. Copyright (2019) American Chemical Society.} \]
It is commonly accepted that a high wavefunction overlap in a QW is preferential in light-emitting devices. We will here use a simplified model to quantify the extent of profit obtained by utilization of a wide QW with a high wavefunction overlap in an LED. The IQE is given by:

\[
\text{IQE} = \frac{\Gamma_{eh} B n^2}{\Gamma_{eh} A n + \Gamma_{eh} B n^2 + \Gamma_{eh} C n^3}, \tag{1}
\]

where \(\Gamma_{eh}\) is the overlap between electron and hole wavefunctions, \(n\) is the carrier density and \(A\), \(B\) and \(C\) are the Shockley–Read–Hall, radiative and Auger recombination coefficient, respectively. Usually, Eq. (1) is presented in a form without the \(\Gamma_{eh}\)—its value is hidden in the values of \(A\), \(B\) and \(C\) parameters. The calculated IQE for both compositions is presented in Fig. 3(a) with the values of the \(A\), \(B\) and \(C\) parameters given in the legend. We have taken these coefficients from Ref. 55 because the authors have calculated \(\Gamma_{eh}\) for the studied QWs and extracted the values of \(A\), \(B\) and \(C\) independent of \(\Gamma_{eh}\). The maximum efficiency is observed in the two presented cases at the same carrier density due to the \(C\) coefficients being equal. However, the efficiency of the green QW is slightly lower due to a lower coefficient of the bimolecular radiative recombination. The regime in which the LEDs operate is at carrier densities beyond the maximum value of IQE—often referred to as the “droop” regime. The reason why the real-life LEDs operate in the droop regime is cost efficiency mandated by the footprint of the device. Even small improvement in the IQE at high carrier density is desirable as it would increase the cost efficiency of LEDs and, most importantly, contribute to decrease in energy consumption on a global scale.

It can be noted from Eq. (1) that the \(\Gamma_{eh}\) terms cancel out and thus the dependence of IQE on carrier density is not influenced by the wavefunction overlap. It is a different mechanism through which wavefunction overlap influences the IQE. The LEDs are operated at a certain current density and wavefunction overlap changes the carrier density for a given current density through the relation:

\[
j = q d_{QW}(\Gamma_{eh} A n + \Gamma_{eh} B n^2 + \Gamma_{eh} C n^3), \tag{2}
\]

where \(q\) is the elementary charge and \(d_{QW}\) is the QW thickness. We can see that in order to decrease the carrier density for a given current density, we can either increase the QW width or the wavefunction overlap. It is here that a high wavefunction overlap is beneficial. It promotes operation at a lower carrier density and therefore closer to the maximum of IQE. In the case of the LDs, the situation is similar. LDs with thin QWs usually operate with a carrier density in the mid 10^{19} \text{ cm}^{-3}. A decrease of the carrier density would allow these devices to operate at a higher IQE as seen in Fig. 4(a).

The reduction in carrier density could in principle be also realized by introduction of additional QWs. However, due the large difference in electron and hole mobilities, carrier distribution is inhomogeneous among the QWs. The last QW has the highest hole density, which results in a lower IQE.

As we have shown earlier there is an extremely large dependence of wavefunction overlap of the excited states on current density (see e.g. Fig. 1(d)). In order to study the impact of utilization of wide QWs on IQE of LEDs, we have used the calculated dependence of \(\Gamma_{eh}\) on current density and calculated the corresponding carrier density using Eq. (2). We performed the calculations for four LEDs with different active region composed of: (1) 2.6 nm In_{0.17}Ga_{0.83}N, (2) 10.4 nm In_{0.17}Ga_{0.83}N, (3) 2.6 nm In_{0.3}Ga_{0.7}N and (4) 10.4 nm In_{0.3}Ga_{0.7}N, in order to study the influence of width and composition of the QW. In this simplified model we had to assume that in each of the QWs there is only one transition. We have chosen the transition with the highest wavefunction overlap. In the case of the 2.6 nm In_{0.17}Ga_{0.83}N QW, throughout the whole current range only the \((\epsilon 1h1)\) transition is taken. However, in the case of the 10.4 nm In_{0.17}Ga_{0.83}N QW the main transition changes from \((\epsilon 2h2)\) to \((\epsilon 2h1)\) at a current density of \(j = 1.6 \text{ kA cm}^{-2}\) as noted with arrows in Figs. 4(b) and 4(c). For the 2.6 nm In_{0.3}Ga_{0.7}N and 10.4 nm In_{0.3}Ga_{0.7}N QWs the wavefunction overlaps of \((\epsilon 1h1)\) and \((\epsilon 2h2)\) transitions were used in the whole current density range, respectively. This approximation causes a...
slight increase in the carrier density in the case of wide QW, where additional transition path would enhance the carrier recombination. In other words, if other transitions would also be used, the IQE of the wide QW would be even higher. The calculated dependence of carrier density on current density is presented in Fig. 4(b). We can see that the highest carrier densities are observed for the thin QW, especially in the case of the In0.3Ga0.7N QW. In the case of the wide QWs there is a substantially lower carrier density at a given current density. This results in a smaller part of carriers recombining through the Auger non-radiative process in the case of wide QWs. We have calculated the dependence of IQE on current density and present it in Fig. 4(c). We observed that, in the case of the QW emitting blue light, the wide QW has a 40% higher IQE then the thin QW at \(j = 1\) kA cm\(^{-2}\). However, in the case of the wide QW, the increase is even higher—the wide QW has a 70% higher IQE than the thin QW. This result shows that a higher advantage from wide QWs can be obtained in spectral region, which is known to suffer from the decrease of IQE due to the built-in electric field.

3. Experimental evidence for emission from excited states

3.1. Dependence of emission properties on thickness of InGaN QW

We prepared a series of QW samples grown by plasma-assisted molecular beam epitaxy in order to verify the theoretical predictions regarding transition through excited states in wide InGaN QWs. Description of the growth details can be found elsewhere.\(^{49}\) The structure consisted of 40 nm In0.08Ga0.92N followed with an In0.17Ga0.83N QW and a 30 nm In0.08Ga0.92N cap. The thickness of the QW was changed from 1.2 up to 25 nm. Figure 5(a) shows an exemplary transmission electron microscope (TEM) image of a 15.6 nm QW. We observed sharp bottom and top interfaces. We observed no signs of V-pit or other extended defect formation. Schematic of the QW structure are presented in the inset to Fig. 5(b). Samples were excited with a 325 nm He–Cd laser at room temperature and the photoluminescence was measured with a 0.55 meter long spectrometer coupled with a liquid nitrogen cooled CCD detector. A microscope objective was used to excite the samples with a circular spot with a diameter of 70 \(\mu\)m. Figure 5(b) presents the photoluminescence intensity for all the samples for two excitation densities. We have observed a very peculiar behavior. In the low excitation regime the PL intensity is the highest for thin QWs and drops significantly for wider QWs. The same behavior was previously reported by others\(^{56,66}\) and was attributed to a decrease of the oscillator strength due to spatial separation of carriers. However, in the high excitation power density regime a different trend can be observed. The photoluminescence intensity is higher in the case of the wider QWs. We attribute this change in trend to screening of the piezoelectric polarization by generated carriers and emergence of recombination path with a high oscillator strength in case of wide QWs.

We would like to comment on the impact of fluctuations of thickness and composition on the photoluminescence. Both of these fluctuations have been observed in InGaN QWs.\(^{22,61–64}\) Figure 5(c) presents the FWHM measured at excitation power density of 60 W cm\(^{-2}\). We predict that if indium fluctuations would influence the FWHM than we would observe a constant FWHM, because in all of the samples indium fluctuations should have the same magnitude. On the contrary, we have observed a decrease of the FWHM of emission spectrum for wider QWs. Such a trend is expected if the major contribution to broadening of the PL spectrum is due to thickness fluctuations. Even small thickness fluctuation on the order of 1–2 monolayers can lead to broadening of the spectrum. Such fluctuations are unavoidable in QWs and were observed also in other material systems such as GaAs/AlAs and GaAs/AlGaAs QWs.\(^{65,66}\)

In thin InGaN QWs, due to the QCSE, a small change in thickness of the QW leads to a substantial change of emission wavelength. Humphreys has calculated that a 1 monolayer change in 3.3 nm thick In0.25Ga0.75N QW leads to a 58 meV change in transition energy between the ground states.\(^{64}\) However, the impact of the thickness variation diminishes in the case of wide InGaN QWs due to screening of the piezoelectric field. Therefore, the QCSE is negligibly small for excited states and the thickness variation has only a small impact by changing the confinement energy. In the case of wide QWs a thickness variation of 1–2 monolayers has almost no impact on emission energy. It is worth noticing that in the case of the intermediate QWs, the emission spectra can be additionally broadened due to simultaneous recombination through multiple states such as \(\epsilon l/h1\) and \(\epsilon 2/h1\). This broadening may change with excitation power, because the
contribution of the individual transitions changes. By analyzing the dependence of FWHM presented in Fig. 5(c) we conclude that the broadening observed for the thin QWs is due to thickness fluctuations. It is worth commenting that QWs with a low FWHM are desirable for applications in LD, as they should provide a narrower and higher optical gain. The impact of QW width on optical gain in LDs will be discussed in Sect. 4.

We have performed time resolved photoluminescence in order to study the dynamics of carrier recombination. All of the samples were measured and the extracted dependence of decay time on QW width is presented in Fig. 6. Interestingly, two trends can be observed. Firstly, as the QW width is increased from 1.2 up to 5.2 nm there is a significant increase of the decay time. In the case of the 5.2 nm QW, values as high as 3 μs were observed. We attribute this increase to a decrease of the oscillator strength due to spatial separation of the ground states. The calculated change of the wavefunction overlap has been shown in Fig. 2 with a dash–dot line. We can see that the \( \langle e_1hl \rangle \) wavefunction overlap significantly drops with the QW width and for a 5.2 nm QW it is close to zero, which results in a slow recombination of carriers. A similar trend has been also reported by others, both in InGaN/GaN and GaN/AlGaN systems.17,19–21,67,68 For thicker QWs a decrease of the decay time can be observed. We attribute this change in trend to an even smaller \( \langle e_1hl \rangle \) wavefunction overlap, which leads to higher carrier population, screening of the piezoelectric field and emergence of recombination path through excited states with a high wavefunction overlap. The fast decay time in wide QWs is evidence for a change in the nature of transition mechanism. The lowest decay time is observed for the 15 and 25 nm thick QW. One could argue that a fast decay rate can be attributed to high non-radiative recombination. However, as we have already shown in Fig. 5(b), the PL intensity in these QWs is the highest, which is a clear indication that the non-radiative recombination is not responsible for the fast decay rate.

Next, we prepared several LEDs with different QW widths in order to study the emission spectra in a wide excitation range. Five LEDs have been grown with QW thicknesses of 2.5, 6.5, 7.8, 12 and 15 nm. The composition of all of the QWs is intentionally the same and equal to 17% of indium.

![Fig. 6.](image) (Color online) Dependence of photoluminescence decay time on QW width. We attribute the initial increase in decay time, marked with a dashed line, to spatial separation of electrons and holes resulting in a decreased oscillator strength. The black, green and red colors represent our interpretation of the main transition path contributing to observed decay. Reprinted with permission from Ref. 49. Copyright (2019) American Chemical Society.

We have measured the emitting spectra for a current density ranging from 0.1 up to 1000 A cm⁻². Selected emission spectra are presented in Fig. 7(a). In three of the samples the spectra are multimode with complex current dependence. We therefore extracted the peak positions of individual modes and show them in Fig. 7(b). We have observed dramatic changes in the emission characteristics between the samples. Based on the difference in the current dependence of electroluminescence we distinguish three QW width regimes, which determine the behavior of the LED: (i) thin—2.6 nm QW, (ii) intermediate—6.5 and 7.8 nm QWs and (iii) wide—12 and 15 nm QWs. We will describe in detail the observed characteristics in the three cases.

In the case of the LED with thin QW we observe emission at 450 nm, which starts to blue shift at a current density of \( j = 4.4 \text{ A cm}^{-2} \). We attribute this shift to screening of the piezoelectric field and reduction of the QCSE. Importantly, the shift does not start immediately, indicating that the carrier density at low currents is insufficient to screen the built-in field.

In the case of the LEDs with intermediate QWs, the emission starts at very high wavelengths, even up to \( \lambda = 580 \) nm in the case of the 7.8 nm QW. As the current is increased, the peak position strongly blue-shifts and additional higher energy transitions appear. The presence of several peaks in the spectrum is an evidence that transitions involving excited states do occur in QW with sufficient width. At high current densities, a high energy peak appears at around 450 nm. Its intensity surpasses the other transitions, while its position changes only slightly with supplied current. We attribute this peak to the \( \langle e_2h2 \rangle \) transition. The fact that it has a strong intensity and does not shift significantly with current is due to almost full screening of the piezoelectric field by carriers located at the edges of the QW.

In the case of the LEDs with wide QWs the situation is different. We do not observe emission at extremely long wavelengths expected for high separation of ground states in wide QW. We therefore conclude that the \( \langle e_1h1 \rangle \) transition has such a low wavefunction overlap that it can be regarded as a forbidden transition and is not present in the spectrum. However, we noticed that a higher current density is necessary in order to observe electroluminescence from the samples with wide QWs than in LEDs with thin and intermediate QWs. We attribute this to initial filling of the ground states and screening of the piezoelectric field. Only after the QWs are filled with a sufficient carrier density the field is screened and efficient transitions through excited states appear. We hypothesize that the increased current density, which is necessary in order to observe electroluminescence, is due to some small escape of carriers out of the QW either through thermionic emission or recombination on defects. One could argue that the field was already screened in the wide QWs prior to supplying current. However, as we will show in Sect. 3.2, the field is initially present in the wide QW and needs to be screened prior to radiative recombination. In the case of 12 nm QW we observe two transitions in the low current regime. At high current density there is only one peak in the 12 and 15 nm QWs and we attribute it to the \( \langle e_2h2 \rangle \) transition. There is almost no shift of the position of this peak, which once again, points to small increase in the
carrier density with current density once the piezoelectric field is fully screened.

To conclude, there are four evidence that we observe efficient recombination from excited states in wide InGaN QWs: (1) higher PL intensity of wide QW at high excitation, (2) a decrease of PL decay time observed for wide QWs, (3) multimode spectrum of intermediate QWs and (4) lack of shift of EL at high injection for wide QWs.

Next, we will discuss two experimental results which give further insight into the mechanism of screening of built-in field inside the wide InGaN QWs. First, we will show that the built-in field is present in the wide QWs prior to excitation. Secondly, we will present results quantifying the strength of the field inside the QW during excitation.

### 3.2. Anomalous photocurrent in pn diodes with wide InGaN QWs

We performed photocurrent studies on devices with thin and wide InGaN QWs and observed a surprising difference in their behavior. Here, we will describe the results for two samples. The first one consists of a 25 nm InGaN QWs, while the width of the QW in the second sample was 2.6 nm. The QWs were placed in p-i-n diodes. The undoped region consisted of a 140 nm In$_{0.08}$Ga$_{0.92}$N.

The samples were excited with light coming from a Xe arc lamp passed through a monochromator. The light was chopped in order to measure the photocurrent with a lock-in amplifier. The spectral dependence of photocurrent measured for a sample with 25 nm wide QW is presented in Fig. 8. We observed a photocurrent flowing in the reverse direction when the excitation wavelength was lower than 410 nm. This is a standard behavior of a photodiode in which the excited electrons and holes are separated by the electric field of the p–n diode. It is important to note that in this regime both the QW and undoped In$_{0.08}$Ga$_{0.92}$N were excited. However, for excitation wavelengths in the range of 410–470 nm the photocurrent flow was in the forward direction. In this wavelength range only the 25 nm In$_{0.17}$Ga$_{0.83}$N QW was excited. Furthermore, the intensity or even the direction of this anomalous photocurrent depended on chopper frequency.
In order to obtain more insight into the time evolution of the anomalous photocurrent we excited the sample with LDs which allowed us to measure its time dependence. Two excitation wavelengths were chosen—400 nm and 430 nm, which allowed us to study both the reverse and forward photocurrent regimes, respectively. Figures 9(a) and 9(b) present the time dependence of the photocurrent generated with 10 ms long laser pulses with excitation wavelength of 400 and 430 nm, respectively. In the case of excitation with a 400 nm laser, in which the photocurrent is in the reverse direction as expected for a photodiode, we observed standard time and power dependence. However, for excitation wavelength of 430 nm we observe a complex dependence of photocurrent on time. In the case of the low excitation power, the photocurrent flows in the forward direction and its magnitude decreases with time. For higher excitation the forward photocurrent is higher but decays faster and eventually its direction switches to reverse. After the pulse is over we observed a sudden increase in the photocurrent in the forward direction and then a decay to zero. On the other hand, a p-i-n diode with a 2.6 nm QW excited with a 430 nm LD does not show any sign of anomalous photocurrent as can be seen in Fig. 9(c).

Our interpretation of the observed time dependence is that inside the wide QW there is the piezoelectric field and the photogenerated carriers are separated into edges of the QW. Electrons flow towards the p-type and holes in the opposite direction, which is consistent with the observed forward direction of the photocurrent. However, it is not the photogenerated carriers that are directly measured. Instead, the photogenerated carriers accumulate at the edges of the QW and change the distribution of the junction field across the whole p-i-n diode. Due to the fact that the diode is short-circuited the changes in the junction field forces a carrier flow to deionize dopants at the edges of the depletion region. It is the flow of carriers out or into the depletion region, which we measure as the photocurrent. A steady state is reached when the photocurrent changes direction to reverse and becomes constant. We interpret this as a state in which the piezoelectric field is screened by carriers accumulated at the edges of the QW. The subsequently photoexcited carriers are extracted from the QW in direction of the junction field of the p-i-n diode. These photogenerated carriers contribute to photocurrent in the reverse direction. Now let us discuss the increase of forward photocurrent after switching off the laser pulse. We interpret this as reduction of the carrier density in the QW. The carriers, which were located at the edges of the QW are escaping via slow recombination or thermionic emission and due to lack of carriers the built-in field returns. Once again the photocurrent we observe is due to carrier transport necessary to change the depletion region of the p-i-n diode and not the carriers from the QW itself.

This experiment shows that even in the case of extremely wide 25 nm QWs the piezoelectric field is present without excitation and that screening occurs only under excitation.

### 3.3. Influence of hydrostatic pressure on optical properties of wide QWs

We have proposed an approach to quantify the electric field in InGaN QWs by measuring the dependence of emission energy on hydrostatic pressure. The transition energy in a QW with built-in electric field can be approximated by:

$$E_{EL} = E_G + E_{conf} + E_{conf}^b - eL_QW[F_{QW} - E_{exc}], \quad (3)$$

where $E_G$ is the bandgap energy, $E_{conf}$ and $E_{conf}^b$ are the confinement energies of electrons and holes, respectively, $L_QW$ is the QW width, $F_{QW}$ is the electric field and $E_{exc}$ is the exciton binding energy. The experimentally measured change of $E_{EL}$ due to applied pressure, which we will later call the pressure coefficient, can be expressed as a sum of two terms:

$$E_{EL} = E_G + E_{conf} + E_{conf}^b - eL_QW[F_{QW} - E_{exc}], \quad (3)$$

where $E_G$ is the bandgap energy, $E_{conf}$ and $E_{conf}^b$ are the confinement energies of electrons and holes, respectively, $L_QW$ is the QW width, $F_{QW}$ is the electric field and $E_{exc}$ is the exciton binding energy. The experimentally measured change of $E_{EL}$ due to applied pressure, which we will later call the pressure coefficient, can be expressed as a sum of two terms:

$$E_{EL} = E_G + E_{conf} + E_{conf}^b - eL_QW[F_{QW} - E_{exc}], \quad (3)$$
\[
\frac{dE_{\text{EL}}}{dp} = \frac{dE_G}{dp} + \frac{dE_{\text{EL}}}{dF_{\text{QW}}} \frac{dF_{\text{QW}}}{dp}.
\]  

The first term describes the change of the bandgap energy with pressure. This term is determined to be equal to \(30 \div 32\) meV GPa\(^{-1}\) based on pressure coefficient for bulk In\(_{0.17}\)Ga\(_{0.83}\)N in which there is no electric field.\(^{51}\) In the following experiment we will compare the measured value of pressure coefficient to the value for bulk In\(_{0.17}\)Ga\(_{0.83}\)N. The second term is causing reduction of the pressure coefficient if built-in electric field is present.\(^{51}\) This is because the electric field increases with pressure and a higher electric field causes a drop in emission energy. The pressure coefficient can be therefore used to study the presence of built-in electric field.

Here, we will discuss experimental results for three LEDs with 2.6, 15 and 25 nm QWs. The emission energies of LEDs were measured in hydrostatic pressure ranging from atmospheric pressure up to 1 GPa. The changes in emission energy in this pressure regime were linear and pressure coefficients were extracted. The dependence of pressure coefficients on current density is presented in Fig. 10(a). In the case of LED with a 2.6 nm QW the pressure coefficient is equal to 17 meV GPa\(^{-1}\) at low current density and increases up to 22 meV GPa\(^{-1}\) for \(j = 250\) A cm\(^{-2}\). Above this current the pressure coefficient stays relatively constant. In the case of wide QWs, both 15 and 25 nm, we observed a much higher pressure coefficient of 32 meV GPa\(^{-1}\), which is very close to the value obtained for bulk In\(_{0.17}\)Ga\(_{0.83}\)N without the built-in electric field.\(^{51}\) In the measured current density range the pressure coefficient remained constant.

We interpret this results based on differences in the strength of electric field in the QWs. In the case of 2.6 nm QW, the pressure coefficient is lower than the bulk value (31 meV GPa\(^{-1}\)) because of the built-in electric field. As the current is increased the measured pressure coefficient approaches the value for bulk InGaN, however, it saturates at a certain value. We interpret it as saturation of carrier density. In the case of the thin QW there is still electric field remaining even at high injection. This is consistent with findings of Kafar et al., who, by comparing emission energies of LEDs and superluminescent diodes, have shown that electric field is not fully screened in thin QW even at current densities as high as 10 kA cm\(^{-2}\).\(^{72}\)

In the case of wide QWs, the value of the pressure coefficient almost exactly matches the value for bulk InGaN, which indicates that the built-in electric field is fully screened even at the lowest excitation. The results of this experiment is not in contradiction with the interpretation of the photocurrent experiment, in which we concluded that the electric field is present in the wide QWs prior to excitation. We have discussed that in wide QWs there is initially an extreme separation of electron and hole wavefunctions, which results in a lack of efficient recombination path. The supplied carriers occupy the ground states and screen the piezoelectric field. Only after the field is screened there appear efficient transitions through excited states. Therefore, in the case of the photocurrent experiment, we observe the process of screening, whereas in the high pressure experiments we observe the steady state after screening. In order to verify this interpretation, we have calculated the band structures of the LEDs with a Drift-Diffusion Poisson Schrodinger Solver created by Yuh-Renn Wu.\(^{73}\) We averaged the electric field in the QW over the whole width and presented its dependence on current density in Fig. 10(b). As can be seen, the field in the thin QW is slowly being screened as the current density is increased. However, in the case of wide QWs, even at very low current densities the field is very low and does not change much with current. It is worth noting that, despite our claim that the piezoelectric field is fully screened, the calculated averaged electric field in 15 and 25 nm QWs in non-zero at high injection. However, this is due to the fact that there are remnants of the piezoelectric polarization present at the edges of the QW (as seen in Fig. 1(b) for a wide QW). In the middle of the QW the electric field is negligible and the excited states which are spread across almost the whole length of the QW are only slightly affected by the electric field at the edges.

The discussed experiments show that in the case of the wide QWs there exists a built-in electric field that gets fully screened upon excitation.

![Fig. 10](image)

Fig. 10. (Color online) (a) Experimentally measured dependence of the pressure coefficient on current density. The shaded area represents the pressure coefficient of bulk In\(_{0.17}\)Ga\(_{0.83}\)N. (b) Calculated dependence of average electric field in the QW on current density. Reprinted with permission from Ref. 51. © The Optical Society.
4. LDs based on wide InGaN QWs

4.1. Influence of QW width on optical gain

LDs are devices, which operate at a relatively high carrier density at which the Auger non-radiative recombination prevails. The laser operation starts after reaching a certain optical gain, which surpasses the optical losses of the cavity. Optical modes propagating in the cavity can reach the threshold optical gain at a certain carrier density. If the optical mode has a high overlap with the QW, the threshold carrier density is lower. However, there is an interplay between the increase in the optical confinement factor ($\Gamma$) and a decrease in carrier density when the QW width is increased. If there would be a linear increase of carriers inside the QW with supplied current, we would observe no change in the threshold current for LDs with different QW width, because the changes in $\Gamma$ would be mitigated by changes in carrier density. However, the III-N LDs operate in carrier density regime in which there is a substantial Auger recombination. The carrier density has a sub-linear dependence on current density as was shown in Fig. 4(b). It is therefore preferential to increase the volume of the QW and decrease the carrier density. It can be done either by increasing the width or the number of QWs. However, as was discussed earlier, a higher number of QWs often leads to inhomogeneous carrier population across individual QWs due to large difference in electron and hole mobilities.\(^{57,74-78}\)

In this case, the QW closest to p-type has the highest carrier concentration and still suffers from the Auger recombination. Alternatively, one could increase the width of the QW. This approach will also lead to a higher wavefunction overlap, as discussed in Sect. 2.1, which ensures a higher efficiency of the QW. It is therefore of great importance to study the influence of QW width on properties of LDs.

In order to verify whether the use of wide InGaN QWs is feasible for constructing LDs, we prepared three LDs emitting in the blue spectral region with similar epitaxial structure apart from the active region. The active region in these LDs consisted of: (a) a multi-quantum-well (MQW) with three 2.6 nm QWs, (b) a single 10.4 nm QW and (c) a 25 nm QW. The threshold current densities of the LDs were 3.2, 2.8 and 3.5 kA cm\(^{-2}\) for LDs with 3 x 2.6 nm, 10.4 nm and 25 nm QWs, respectively. The slope efficiencies were equal to 0.40, 0.38 and 0.42 W A\(^{-1}\). The best results were obtained for the LD with 10.4 nm QW. However, as can be seen the parameters important for the operation of LDs do not change much with the QW thickness. This might be a surprising result for LDs based on material with high piezoelectric polarization. However, if we consider that the polarization field in the wide QWs is almost entirely screened, such a result is expected.

In order to obtain insight into the role of QW width we measured the optical gain using the Hakki–Paoli technique.\(^{79,80}\) We used a 1 meter long spectrometer with a 3600 mm\(^{-1}\) grating and a CCD camera to collect the amplified spontaneous emission spectra to derive the modal gain. The optical gain spectra collected at various currents for the three LDs are presented in Fig. 11. Internal losses in the three LDs are comparable and range from 19 up to 24 cm\(^{-1}\).

In Fig. 12 we present the dependence of the maximum modal gain on current density for the three LDs. The extracted differential modal gain d$G$/d$j$ is equal to 10.4, 13.8 and 11.7 cm kA\(^{-1}\) for LDs with three 2.6 nm, 10.4 nm and 25 nm QWs, respectively. As can be seen both LDs with wide QWs have higher differential gain then the LD with thin QW. This clearly shows that the wide QWs, especially the 10.4 nm one is better suited for application in LDs then the commonly used thin QWs.

The magnitude of the optical gain is a product of the material gain and confinement factor. In order to obtain insight into the material gain we used a one dimensional waveguide solver to calculate the confinement factors.\(^{81}\) The calculated confinement factors are equal to 0.027, 0.043, 0.125 for LDs with 3 x 2.6 nm, 10.4 nm and 25 nm QWs, respectively. We can now calculate the differential material gain by dividing the differential modal gain by the confinement factor and obtain d$G$/d$j$ of 383, 322 and 93 cm kA\(^{-1}\) for LDs with 3 x 2.6 nm, 10.4 nm and 25 nm QWs, respectively.

The lower values of differential material gain in LDs with wide QWs shows that these LDs operate on lower carrier density as expected from analysis performed in Sect. 2.2 and shown in Fig. 4(b). The fact that the wider QW operate at a lower carrier density should not be surprising. However, it is important to note, because it ensures a lower part of carriers in the wide QW to recombine non-radiatively through the Auger process. Thus, the LDs with wide QW have a higher differential modal gain.

4.2. Long wavelength LDs

We now see that in the case of blue LDs the wide QWs can be successfully used. The excited states in a wide QW can deliver a higher differential gain then what is observed in LDs with thin QWs. However, as discussed in Sect. 2.2, even higher improvement in the performance is expected in QWs with higher indium content. Therefore, it is of great importance to test this prediction on long wavelength LDs. In the case of cyan and green LDs there is an additional detrimental factor which decreases the differential gain—namely the decrease of the confinement factor. This happens due to decrease of the refractive index contrast between alloys as the emission wavelength increases. Once again the confinement factor can be easily increased by adding additional QWs or increasing the width of the QW. Here, we will show what is the impact of wide QWs on gain in long wavelength LDs.

We have prepared two LDs emitting in the cyan spectral region.\(^{49}\) The active region of the first one was composed of three 3 nm thick QWs separated by 7 nm QBs. The second LD had a single 10.4 nm wide QW. The indium content in the QWs was 24%. The calculated confinement factor was 0.019 and 0.028 for the thin MQW and wide QW structures, respectively. The threshold current density for the MQW design was $j_\text{th} = 20$ kA cm\(^{-2}\).\(^{82}\) However, in the case of the LD with a wide QW we observed $j_\text{th} = 5.5$ kA cm\(^{-2}\). This is a stunning difference between the design with thin and wide QW and we will discuss its origin.

The optical gain spectra of the LD with wide In$_{0.24}$Ga$_{0.76}$N QW is presented in Fig. 13. The differential gain for the two LDs is presented in Fig. 14. We observed a staggering difference in the rate at which the gain increased. The differential gain values were equal to 2.2 and 6.5 cm kA\(^{-1}\) for LDs with three 3 nm and 10.4 nm QWs, respectively.

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It is extremely interesting to see that the increase in
differential gain due to utilization of a wide QW is higher
in LDs with a higher indium content in the QW. This is a
consequence of the decrease of the wavefunction overlap
between the ground states with indium content. However, the
wide QWs operate on the excited states, and these can have a
higher overlap for high indium content QWs as shown in
Fig. 3(b). Therefore, the wide QW operates on much lower
carrier density than the thin QW, leading to reduction of the
part of carriers recombining through the non-radiative Auger
recombination.

The change in the differential gain is strikingly high,
almost threefold. Such a high increase is not predicted by the
sole change in the wavefunction overlap and confinement
factor between three 3 nm thick and a single 10.4 nm QW.
However, if we consider that there is inhomogeneous
distribution of carriers among QWs in the device with
MQW and one of them gets preferentially populated then
the efficiency of the QW drops. Additionally, the confinement
factor would be lower than calculated. We expect that
this is the cause of the observed high magnitude of change in
the differential gain between LD with thin and wide QWs.

4.3. Comparison of lasing spectra of LDs with thin
and wide QWs
We observed an interesting difference in the lasing spectra
between LDs with thin and wide QWs. It is commonly

Fig. 11. (Color online) Measured optical gain spectra of LDs with active region composed of: (a) three 2.6 nm QW, (b) a single 10.4 nm QW and (c) a 25 nm QW. The blue circles, green triangle and red diamonds denote the values of optical gain used to derive the differential gain. Reprinted with permission from Ref. 52. Copyright (2019) The Japan Society of Applied Physics.

Fig. 12. (Color online) Dependence of maximal modal gain on current density for three LDs. The dashed lines are linear fits used to extract the differential gain values. Reprinted with permission from Ref. 52. Copyright (2019) The Japan Society of Applied Physics.

Fig. 13. (Color online) Optical gain spectra of long wavelength LD with a single 10.4 nm QW collected at current densities ranging from 0.33 to 5.33 in steps of 0.33 kA cm$^{-2}$. Reprinted with permission from Ref. 49. Copyright (2019) American Chemical Society.

Fig. 14. (Color online) Maxima of optical gain of cyan LDs with different QW design. Linear fits were used to extract the differential modal gain. Reprinted with permission from Ref. 49. Copyright (2019) American Chemical Society.
reported that InGaN LDs have a complex multimode spectra with a separation between peaks, which is much larger than expected from the length of the Fabry–Perot resonator. \cite{83–86}

In Fig. 15(a) we present an exemplary lasing spectra of LD with three 2.6 nm QWs. As can be seen there are two main peaks with a spacing of $\Delta \lambda = 0.31 \text{ nm}$. Between these two modes additional small peaks can be observed—these are the modes of the Fabry–Perot resonator, however, they are heavily damped. On the other hand, in the case of LDs with a 10.4 nm thick QW the lasing spectra has numerous modes as shown in Fig. 15(b). The spacing between these modes is $\Delta \lambda = 0.047 \text{ nm}$ as expected from the Fabry–Perot resonator.

A model was proposed by I. V. Smetanin and P. P. Vasil’ev to explain the observed intensity distribution. \cite{87} They predicted a modulation in optical gain due to spatial separation of electrons and holes in the active region, an inherent property of InGaN QWs. The carriers at the edges of the QW form 2D oscillation frequency depends on the spatial separation of electrons and holes. \cite{87} In the case of the wide QWs, the carriers occupying the ground states are much more separated than in the thin QW, as was discussed earlier and shown in Fig. 1(c). The carriers occupying the excited states, on the other hand, are much more evenly distributed along the whole width of the QW. We have calculated the plasma response of carriers at the ground states assuming $n_{pl} = 1.65 \times 10^{13} \text{ cm}^{-2}$ and a spatial separation of 9 nm. \cite{52} The resulting modulation of optical gain was $\Delta \lambda = 6.7 \text{ nm}$, which is much greater than the width of the optical gain. Therefore, in the case of the LDs with wide InGaN QWs, the lasing spectra is not modulated by the plasma oscillations. The presented difference in the lasing spectra between LDs with thin and wide QWs shows that the model proposed by I. V. Smetanin and P. P. Vasil’ev is correct.

5. Summary

In this review paper we have discussed the recent advancements in comprehension of the physics of carrier recombination in wide InGaN QWs. We have shown that, contrary to what could be expected from the large piezoelectric field present in III-N material system, there is a substantial wavefunction overlap between excited states in a wide InGaN QW. However, this effective transition path is present only under excitation. Initially, due to almost zero overlap between the ground states, the carriers do not recombine but accumulate leading to screening of the built-in electric field. The distribution of the excited states changes and an effective transition path appears. At the same time the wavefunction overlap between the ground states remains marginally small.

We have discussed several experimental evidence for transitions between excited states in wide InGaN QWs. Additionally, we have shown that built-in electric field is present in wide QW prior to excitation and gets screened as soon as carriers are supplied.

Finally, we have demonstrated devices utilizing the wide InGaN QWs. In particular, we have compared how the optical gain is formed in LDs with thin and wide InGaN QWs. We have shown that an exceptionally high increase in the differential gain is observed for the long wavelength LDs, which leads to a substantial decrease of the threshold current density.

We believe that the presented results will promote further research on the physics of the wide InGaN QWs and enhance the efficiency of GaN-based optoelectronic devices. Especially in the green spectral region, the utilization of wide InGaN QWs can bring a substantial increase in efficiency.

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