Influence of carrier statistics on InGaN quantum dot device performance

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ABSTRACT

In this work InGaN quantum dots (QDs) in GaN matrix formed during strain induced phase separation were investigated. We show that although electron – photon interaction rate in residual quantum well (QW) InGaN is high, carrier capture to QD levels and carrier escape from QD levels to the QW is slowed presumably due to large energy distance between the QD levels and between the QD levels and the QW band. This leads to deviation of quasiequilibrium of carrier distribution in QDs even at temperature higher than 300K. We also modify rate equation model taking into account this deviation. In this model we consider the QW as a quasiequilibrium reservoir, but carrier statistics in the QDs is calculated in term of nonequilibrium statistics of Sah-Noyce-Shokkley-Read centers with strongly inhomogeneous localization depth. This model describes lasing line broadening in terms of carrier burning and formation of multimode emission.

Keywords: quantum dots, InGaN, carrier statistics, localization, semiconductor laser

1. INTRODUCTION

Heterostructures with quantum dots (QD) attract more and more attention of investigators due to their unique properties such as complete spatial carrier confinement and discrete electronic spectra, both not pertaining to other kinds of heterostructures. As distinct from another quantum confining system where infinite carrier motion at least during one direction and so quasicontinuous electronic spectra exists, in QDs energy distance between the ground state and the first excited state can exceed the thermalization energy $k_B T$ ($k_B$ - is Boltzmann constant $T$ - temperature). Without any carrier pumping carrier distribution in QD levels obeys the Fermi rule. When the pumping is applied two cases can be distinguished. In case of high probability of intraband transitions as compared with recombination rate, the carrier distribution is quasiequilibrium. It means that within one band (for example conductivity band (CB)) carrier redistribution rate is much higher than rate of carrier leaving from and coming by means of recombination and pumping. Hence, carrier relaxation within this statistical subsystem is so high as compared with processes of exchange with other subsystems that local equilibrium must be established in this band. Analogous reasoning can be made for the valence band (VB). Thus, differing chemical potentials (quasi Fermi levels) can be found for each band. In other case, when carrier redistribution within band is not quick enough this approach is not valid. In the opposite case, when recombination rate is much higher than carrier redistribution, another approaches are suggested.

In quantum wells redistribution times are known to be fast. These processes are usually assisted by electron – phonon interaction, and in case of quasicontinuous electron spectra probability of these processes is high because there is no exact requirement for phonon energy. At the same time in QDs the interband transitions are limited by low probability of absorption or emission of a phonon (in case of large energy distance even a few phonons) with corresponding energy. It can also lead to the so called bottleneck effect and nonequilibrium carrier distribution that was observed in some QD systems at corresponding conditions. The carrier relaxation can also be assisted by Auger processes but this effect is significant only in narrow bandgap semiconductors and falls quickly with increase of the bandgap. Furthermore, the Auger processes are also typical for high excitation densities, however the measurements in present work were made under low pumping density (except lasing measurements).

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In works by Asryan and Suris\textsuperscript{3,12} optical properties of inhomogenously broadened arrays of QDs were considered in detail and the following criteria of carrier quasiequilibrium was given:

\[
T > T_q = \frac{1}{k_B} \max \left( \frac{\Delta E_{e}}{\ln(\sigma_{e}v_{n}N_{c,v}^\tau_{QD})}, \frac{\Delta E_{p}}{\ln(\sigma_{p}v_{n}N_{c,v}^\tau_{QD})} \right)
\]  

(1)

Here \(\Delta E_{e,p}\) – energy distance between levels of electrons and holes in the QDs and quasicontinuous electron spectra with density \(N_{c,v}\) for the CB and the VB correspondingly, \(\sigma_{e,p}\) – cross sections of electron and hole capture \(v_{n,p}\) their thermal velocity, \(\tau_{QD}\) – radiative recombination time in QDs.

The large energy distance in QD systems compared with thermalisation energy \(k_B T\) can serve for different applications. For example, it decreases contribution of transitions of excited states and the quasicontinuous spectra in spontaneous emission in lasers operating on QD ground states because of low occupation of these accessory levels\textsuperscript{3,14}. In case of quasiequilibrium statistics this accupation obeying Fermi law can easily be calculated. We have recently shown that in case of the quasiequilibrium distribution contribution of nonradiative recombination can be calculated that allows simulating efficiency and threshold characteristics in quantum dot lasers\textsuperscript{15,16}. We have also shown that the great distance between QD ground state and the matrix levels allows suppressing nonradiative recombination in the matrix owing to low carrier occupation in it\textsuperscript{17}.

Recent time technology of devices operating on single quantum dots has been developing. This technology is based on employment of nanoscale devices and photonic crystals. For some applications, such as single photon sources\textsuperscript{18} it is urgent to have only ground states populated to control photon precisely. Again, the undesirable population of the excited states can be decreased by increasing energy distance between the QD levels and (or) decreasing of operating temperature. The resonance tunneling carrier injection is considered to be the most attractive in this case\textsuperscript{18} so if carrier tunneling plus carrier recombination time is less than carrier redistribution time, carrier redistribution to other levels will be suppressed even at higher temperatures.

At the same time, carrier behavior in case of nonequilibrium carrier distribution still remains relatively little known. It may be since most of well-known QD system have quasiequilibrium carrier distribution around room temperature (the temperature in which convenient light emitting devices operate). Thus it is also little known about influence of deviation of equilibrium on QD optical properties\textsuperscript{10,19,20}.

In present work heterostructures of wide bandgap semiconductor compounds – III-group nitrides were investigated. This system is characterized by large values of band offsets in heterojunctions\textsuperscript{21} that allow achieving large value of localization energy in quantum confining structures due to deep localization potential. In case of ultra small localizing structure spatial dimension, large energy distance between different electron levels is also achievable. Although great number of investigations of quantum confining structures based on III – nitrides, particularly disordered InGaN quantum wells and InGaN quantum dots\textsuperscript{22,23,24,25} have been carried out, there is little known about intrinsic QD structure\textsuperscript{26} determining the mentioned properties such as the distances between the ground and the excited states as well localization energy between the QD levels and the quasicontinuous spectra.

A peculiarity of ultrathin InGaN layers is a presence of strong built-in fields in the heterointerfaces\textsuperscript{27,28,29}, resulting in the quantum confinement Stark effect\textsuperscript{29}. In this case decrease of optical junction energy\textsuperscript{29} may be accompanied by decrease in radiative recombination time due to spatial carrier separation. However, time resolved photoluminescence (PL) data demonstrate saturation of this recombination probability decrease when the transition energy is less than some value\textsuperscript{30,31}. Consideration of emission and adsorption spectra demonstrates the Stokes shift\textsuperscript{31} indicating that the emission occurs from bandtail localizing carriers. Other data such as resonance excitation at low temperature proofs that this bandtail consists of array of discrete levels acting as quantum dots. Origin of this QD formation is strain induced phase separation leading to formation of fluctuations of In concentrations. This fluctuation distributions obey error function (see exp. 11 below)\textsuperscript{22,23}. Electron spectra of states produced by carrier localization in these fluctuations can also be approximated using this law. Scale of this tail can vary according to growth conditions and postgrowth treatment\textsuperscript{33,34}.

In present work we investigated carrier statistics in structures containing InGaN QDs. PL, electroluminescence (EL) and photocurrent (PC) data obtained at temperature range from 80K to 600K are considered and possibility of deviation from quasiequilibrium distribution is discussed. In this work we also discuss how much PC spectra reflect electronic spectra in these structures. In section 2 details of experiment are described. In section 3 the quasiequilibrium approach is considered and in section 4 it is shown that for some InGaN/GaN QD structures this approach does not agree with experiment even at temperatures higher than 300K, indicating on deviation from the quasiequilibrium. Approach taking into account deviation from the equilibrium is formulated in section 5. In terms of this approach each QD is considered as a separate subsystem and this approach was applied for simulation of lasing spectra that are compared with experimental spectra in section 6.
2. EXPERIMENTAL DETAILS

In this work we investigated light emitting structures grown by MOCVD method on AIX 2000HT growth machine. The structures were grown on (0001) sapphire substrates. After nucleation layer deposition 3.5 μm GaN:Si layer was grown. In laser structures short period (5nm, 120 periods) AlGaN/GaN superlattices that served for optical confinement were then grown. In light emitting diodes the superlattices were not grown. Then in all structures 20 nm AlGaN current blocking layer was deposited. This current blocking layer was grown in order to suppress hole injection to area outstanding from active region. Then, the active region consisting of five InGaN QD layers with 3 nm average widths separated by 7 nm GaN spacers was grown. After that, 20 nm AlGaN:Mg current blocking layer was grown to prevent electron leakage. The structures were capped by 250 nm of GaN:Mg p-type contact layer. In order to increase PL pumping efficiency in some structures this cap layer was etched down to AlGaN:Mg layer. In this work we investigated structures with two kind of active region (A and B). During the growth of the structures of kind B after InGaN deposition there were made growth interruptions enchanting formation of In – reach areas and so increasing QD localization depth. In the structures of kind A the QDs formed without any especial treatment and so QDs with less average localization depth were formed.

Optical properties of the structures were investigated by PL, EL and PC spectroscopy methods. CW HeCd and pulse N₂ lasers with maximal pumping power density of 100 W/cm² and 100 kW/cm² correspondingly were used for PL excitation. PC was excited by Xe lamp. Single gate monochromator was used for optical spectroscopy measurements while PL and EL were detected by photomultiplier and PC was detected using SR810DSP lock – in amplifier. Resistive heater was used for sample heating up to 600 K and liquid nitrogen cryostat was used to decrease sample temperature down to 80 K. Although at room temperature peak positions of the samples was almost the same (see fig. 1 below), average In concentration controlled by X-ray characterization was much less in A-type samples. Since the Stoke’s shift discussed above is stronger in B-type samples, we concluded that they contained QD with greater localization depth, that allowed to achieve the same emission wavelength with less average In concentration (QDs provide less contribution in average In – concentration than QW) We will consider optical properties of these structures in detail below.

3. QUASIEQUILIBRIUM APPROACH

A convenient method for consideration of electrical and optical properties of both bulk semiconductors and heterostructures is the quasiequilibrium approach which also utilizes the Fermi golden rule. According to this approach the VB of the bulk material together with VB states of QWs, quantum vries or QDs (if any) can be considered as quasiequilibrium subsystem. At the same time, CB of bulk with CB states of confining areas is considered as another quasiequilibrium subsystem. Each of these subsystems is characterized by its own chemical potential (or quasi Fermi level position). In case of lack of external pumping the whole system is equilibrium and the quasi Fermi levels coincide with each other. There is also equilibrium between carriers, photons and phonons obeying corresponding distribution function. When the external pumping is applied and a constant temperature there is a deviation from the total equilibrium. If the temperature is high enough and electron – phonon interaction rate is also high enough thermal equilibrium between carriers and phonons remains although the chemical potentials are separated for CB and VB. Since the Fermi functions determine carrier population spontaneous emission rate according to Fermi golden rule can be expressed as follow:

\[
E_{SP}(E) = \frac{4\pi n e^3}{m^2 \epsilon_0 h^2 c^3} \int_{-\infty}^{\infty} \rho_v(E') \rho_v(E') M(E', E'')^2 f_v(E') f_h(E'') dE'
\] (2)

Here E is the transition energy, \(\vec{n}\) - refractive index, m – mass of electron, \(\epsilon_0\) - vacuum dielectric constant, h – Planck constant, c – the velocity of light, \(E'' = E' - E\), M – matrix element of transition from energy level \(E'\) to level \(E''\). \(f_{v,h}\) - are distribution of the carrier population that obey Fermi law in the quasiequilibrium case.

At the same time, absorption of light with photon energy E will be expressed as follow

\[
\alpha(E) = \pi e^2 n \frac{a}{h^2 c E} \int_{-\infty}^{\infty} \rho_v(E') \rho_v(E') M(E', E'')^2 (f_v(E') + f_h(E'') - 1) dE'
\] (3)

The eq. (2), (3) are a consiquence of Einstein relations and can be derived from quantum electrodynamics principles and Plank distribution law for photons. These equations were obtained by Stern for bulk semiconductors, however they can be generalized for spontaneous emission and absorbance in quantum confining system. As a consequence of this approach there is the definite relation between spontaneous emission and absorption spectra.
Here \( f_{c,h} \) are again Fermi functions, however according the Fermi golden rule (2)-(4) can be satisfied also for another distribution functions, i.e expressions (2) and (3) are correct for any other thermodynamic system condition, but in (4) the carrier distribution functions for absorption and for emission cases must be the same, that is not always true.

In work [3], in particular expressions for optical gain and spontaneous emission in QD arrays with a dispersion in optical transition energy are presented. In this case the quasiequilibrium carrier statistics in the QD levels was obtained as a consequence of Sah-Noyce-Shokkley-Read trapping centers statistics. The fast capture – escape processes according to (1) allow considering the system of QDs and matrix as containing two CB and VB subsystem with common quasi-Fermi levels for each of the subsystems.

To keep energy balance in the system, power coming to system by pumping must be equal the power leaving system by light emission. It is convenient to employ rate equation formalism for calculation of electron, hole and photon concentration in the system, as well quasi Fermi levels positions. (See for example [37]). Advantage of this approach is that it allows easily considering measurable quantities such as spectral dependences of light emission and its dynamics (for example rise and decay) in systems with complex optical resonator, complex carrier confining and so complex electron state and photon mode spectra.

To describe processes occurring in our structures we employed relatively simple model. According to this model only optical transitions inside QD were allowed. Concentration of the QDs decreases with transition energy decrease according to error function (see eq. (11) below) Sunce there is strong superexponential dependence on energy we also neglected contributions of excited states on emission and charge because it is much less than the contribution of ground states of QDs with less transition energy. QD levels position relatively matrix bands we accounted according to band offset in heterointerfaces. The following rate equations can be obtained for photon concentration \( P \) in a mode of flat resonator:

\[
\frac{dP}{dt} = \frac{\rho_{QD} \left[ f_c f_h + (f_c + f_h - 1) \right]}{\rho_{mod} \tau_r} PS \frac{P}{\tau_{ph}}
\]

Here \( \rho_{QD} \) - sheet QD density with corresponding transition energy, \( \tau_r \) - so called radiative recombination time that is reverses probability of QD electron – hole pair interaction with electromagnetic field oscillation in resonator modes with density \( \rho_{mod} \) in scale of energy. \( S \) – resonator area, \( \tau_{ph} \) - photon lifetime in the resonator (according to its Q - factor). Expressions for electron and hole occupation in QD levels is following:

\[
\begin{align*}
\frac{df_e}{dt} &= \sigma_{n} \nu_{e} \left[ n \left( 1 - f_e \right) - n_{e} f_e \right] \frac{1}{\tau_r} \left[ f_c f_h + \left( f_c + f_h - 1 \right) \right] PS \\
\frac{df_h}{dt} &= \sigma_{p} \nu_{p} \left[ p \left( 1 - f_h \right) - p_{h} f_h \right] \frac{1}{\tau_r} \left[ f_c f_h + \left( f_c + f_h - 1 \right) \right] PS 
\end{align*}
\]

\[
\begin{align*}
\text{where} \quad n_{e} &= N_{e} \exp \left( \frac{\Delta E}{k_{B}T} \right) \\
\text{and} \quad p_{h} &= N_{v} \exp \left( \frac{\Delta E}{k_{B}T} \right)
\end{align*}
\]

In (6) the first term in the right-hand member take account of carrier capture and escape while the second one take account of carrier recombinaction and re-excitation.

Another advantage of the approach is also that in stationary case the left-hand member of equations (5), (6) is equal zero and they turn to algebraic equations.

However, as it was mentioned above these equations usually take into account equilibrium between all carriers populating QDs separately for CB and for VB. If the interaction between carriers and phonons is kinetically slowed this equilibrium can be broken. It is however important to stress that Sah-Noyce-Shokkley-Read approach permits deviation of equilibrium between the quasicontinuous electron spectrum and QDs. We will consider this case below.

4. DEVIATION OF THE QUASIEQUILIBRIUM

Let us consider PC measurements in case of quasiequilibrium. In case of PC measured without external bias and negligible loading resistance, quasi Fermi level for electrons coincide with quasi Fermi level for holes.

Since the thermal redistribution is fast, electron – hole pairs excited by external lighting do not break this equilibrium. The excited carriers recombination will be negligible small because they will efficiently escape for
escape time is shorter than recombination time. Thus, the excited carriers must efficiently leave QD levels and give contribution to photocurrent with efficacy equal for every QDs. As a consequence, in case of quasiequilibrium distribution photocurrent spectra is proportional to absorbance spectra in QD containing medium to coefficient of photoresponse that is common for every QDs. As it was mentioned above relations between emission and absorbance spectra can be obtained using generalized eq. (2) and (3).

In case of low resonator Q- factor and low photon concentration, there is low photon absorbance so spontaneous emission is equal external optical emission from the sample. Hence, the first term in square brackets In eq. 5 is much more than another terms, so external emission can be obtained:

\[ I_{\text{emission}}(E) = \frac{P(E)\rho_{\text{mod}}}{\tau_{ph}} = \frac{\rho_{\text{QD}}}{\tau_e} f_e f_h \quad (7) \]

at the same time, the second term in square brackets expresses photon absorbance rate in the present mode:

\[ \alpha_{\text{mod}}(E) = \frac{\rho_{\text{QD}}}{\rho_{\text{mod}}\tau_e} (f_e + f_h - 1)PS \quad (8) \]

In case of low carrier pumping power the electron quasi-Fermi level situates significantly lower than area of CB QD states and the hole quasi Fermi level situates significantly higher than VB QD states. In this case the Boltzmann statistics is present and carrier population obeys the exponential law:

\[ f_e = \exp\left(-\frac{E_e}{k_B T}\right); \quad f_h = \exp\left(-\frac{E_h}{k_B T}\right) \quad (9) \]

(Here \(E_{e,h}\) - QD electron and hole levels positions)

One can found relation between absorbance and emission from (7) – (9):

\[ r_{\text{sp}}(E) = \text{const} \cdot E^2 \exp\left(-\frac{E}{k_B T}\right) \alpha_{\text{mod}}(E), \quad (10) \]

that is analogous to (4).

Fig.1 experimental PL spectra and spectra extracted from PC spectra using quasiequilibrium approach for a) A – type structure with relatively shallow QDs and b) B – type structure with deep QDs.

EL emission spectra and the spectra obtained from (10) are shown in fig.1

One can see good agreement between experimental and calculated spectra for structure of type A (fig 1 a) indicating on almost quasiequilibrium carrier distribution in the structure with shallow QDs. However, strong disagreement is seen for B – type structure that indicates on significant deviation from the Boltzmann statistics. We associate this behavior with slow escape times as compared with recombination times according to (1). In this case:

- Photocurrent spectra do not correspond absorbance spectra. This is because in the case of low probability of carrier activation electron – hole pairs excited during photocurrent measurements linger on QD states for the times that are relative with recombination time and so they can re – recombine20.
- Emission spectra does not satisfy (7) with Fermi – functions substituted as carrier distribution \(f_{e,h}\) .
In order to confirm the former statement let us consider PC spectra of B – type structure obtained at different temperatures (fig.2) we can see that the spectrum ‘tail’ at low energy side elongates with temperature increase. We believe that it is due to increase of carrier escape probability from deep QDs. As it can be seen in fig. 1 b there is complete agreement with eq. (10) meaning that quasi-equilibrium statistics becomes established with temperature increase to 600 K. It also means that carrier activation becomes efficient at 600K and in this case PC spectrum is proportional to absorbance spectra.

Since the absorbance spectrum allows estimating electron spectrum, the spectrum ‘tail’ at low energy side (as well as band tail) can be approximated by error function\(^ {23}\). However, according to above discussions it is important to stress that this absorbance spectrum can be obtained from measurable PC spectrum only when quasi-equilibrium statistics is confirmed. Taking it into account we approximated the PC spectra tails for structures of A and B types by the error function\(^ {23}\):

\[
\rho_{\text{QD}}(E) = \rho_0 \exp \left( -\frac{(E - E_0)^2}{\sigma^2} \right)
\]  

The broadening parameter \(s\) was 70 and 100 meV for A-type and B-type structures correspondingly (fig.3). It is expected result that the \(s\) – parameter is larger for structure of type B since these structures were grown under regimes stimulating disordering.

Dependences of PL peak positions on pumping power (or emission intensity) confirm deviation of Boltzmann statistics during emission processes. Since there is nonradiative recombination in the structures it is not always correctly to draw the dependences on pumping power because of the nonradiative recombination varying for different structures and different temperatures. However it seems to be quite correctly to draw the PL peak position versus emission intensity owing to direct dependence of the intensity on QD level occupation (see eq.7). As it can be seen in fig. 4 a there is a plateau in the dependences unless pumping power is higher than 60W/cm\(^2\). This corresponds to nondegenerate carrier population\(^ {22}\) and is typically observed in case of Boltzmann statistics. There is a strong blueshift at higher pumping power corresponding to transition to degenerate carrier population that is due to bandfilling. Since in this transition the QD population is comparable with unity one can estimate the QD density by eq.7. The estimated QD density is in agreement with data obtained by transmission electron microscopy from analogous structures\(^ {2,55,2,60,2,65,2,70,2,75,2,80,2,85,2,90}\). In fig.4 b one can see that there is another behavior in the structure of type B. Strong blue shift can be seen again at pumping power higher 60 W/cm\(^2\) at room temperature. However the plateau is not exact at lower pumping power range at room temperature. Furthermore, the plateau is seen at 600K when the quasi-equilibrium is believed to be established. This behavior could be explained by more lingered bandtail in B – type structure, however there is also plateau at low temperature (81K) while in the quasi-equilibrium case the dependence must be even stronger at low temperature on the contrary\(^ {23}\). Thus, we believe that these data confirm nonequilibrium carrier population at room temperature in structure of type B during light emission process. At the same time there is equilibrium like behavior at 600K (analogous with dependence for A – type structure at 300 K) that agrees well with data in fig.1. To describe the B – type structure behavior at lower temperature especial calculations are necessary.

5. RATE EQUATIONS FOR NONEQUILIBRIUM QD SYSTEMS

As it was seen in previous section the quasi-equilibrium approach is not valid for deep InGaN QDs even at temperatures higher than 300K. Thus the approach taking into account deviation from equilibrium between QDs is here demanded. As we have recently shown\(^ {38,39}\) for shallow QDs, no change in spectra shape at the energies higher than PL peak position with temperature increase indicates on quasi-equilibrium carrier statistics inside the residual quantum wells.
and shallow QDs. Also, in the structures with deep QDs spectra shape does not change significantly with temperature in diapason of energy higher than PL peak position. The main mechanism of carrier scattering in vurtzite crystals near room temperature is known to be interaction with optical phonons. Typical scattering times for structures with quasicontinous electron spectra amount $10^{-13}$ s. So we believe that carrier statistics in residual InGaN QW can be considered as quasiequilibrium. However, in the QDs the relaxation times are known to be longer probably due to requirement of energy agreement between phonon and intraband transition. That can be the reason of carrier statistics deviation from quasiequilibrium between deep the QDs (and the QW). According to Sah-Noyce-Shokkley-Read approach a stationary state of system with carrier capture, escape, recombination and absorption can be expressed by following stationary rate equations:

\[
\sigma_n v_n \left[ n(1-f_e) - n_i f_e \right] - \frac{1}{\tau_e} \left[ f_e f_h + (f_e + f_h - 1)PS \right] = 0 \tag{12 a}
\]

\[
\sigma_p v_p \left[ p(1-f_h) - p_i f_h \right] - \frac{1}{\tau_h} \left[ f_e f_h + (f_e + f_h - 1)PS \right] = 0 \tag{12 b}
\]

In work [3] the extreme cases are considered:

- In case of low carrier recombination rate ($1/\tau_r$) as compared with carrier escape rate $\sigma_n v_n P_1$, $\sigma_p v_p P_1$, the second term responsible for recombination is negligible low and the solution of (12) gives quasiequilibrium carrier population obeying Fermi or Boltzmann law.
- In other case, if recombination rate is much quicker than escape time the first term that is responsible for carrier escape is negligible.

Although, intermediate case was not considered there perhaps because of the difficulties to obtain analytic solution, this problem can be derived numerically. Let us consider carrier concentrations in QW designated as $n$ and $p$ for electrons and holes accordingly to (12). Because of lack of equilibrium, the charge neutrality must not be fulfilled here. However, as a consequence of Kirchhoff law electron and hole streams must be equal. These streams are also equal to injection current $I$. The whole carrier outflow from QW by carrier capture and carrier inflow by carrier escape can be be calculated integrating the first terms in equations (12). The carrier recombination in QW can be here taken into account as a negative part of $I$. Then, the following stationary rate equation can be written for carrier concentration in the QW.
The equations (12), (13), and stationary equation (5) form rate equation system determining parameters of spectral distribution of carrier population and optical properties in structure containing widely inhomogeneously broadened QD array. In quasiequilibrium case these equations turn to well known equations from\(^3\). In case of transition to nonequilibrium case, when the values \(\sigma_n v_n n_1\), \(\sigma_p v_p p_1\), and \((1/\tau_p)\) are comparable, the solutions of this system of equations predict the properties different from properties of quasiequilibrium system. For example we will discuss in the next section influence this statistics on lasing.

5. LASING SPECTRA

Spectral intensity of the emission is proportional to ratio between photon density in a given mode and photon lifetime in the resonator \(\tau_p\), multiplied by photon mode density. From (5) we obtain

\[
\frac{P}{\tau_{ph}} \rho_{\text{mod}} = \frac{1}{\tau_{ph}} \frac{\rho_{QD}}{\tau_{ph}} \left( \frac{1}{\sigma_n v_n} \frac{1}{\tau_{ph}} + \frac{1}{\tau_{ph}} \frac{1}{\rho_{QD}} \right) (f_e + f_h - 1)
\]

(14)

We can see that when carrier populations in QDs with a given transition energy achieve some values the denominator turns to zero corresponding unlimited emission intensity at given wavelength. In case of perfectly quasiequilibrium carrier distribution on QD levels and error function like electron spectra the second term of the denominator has a maximum in a transition energy that corresponds the maximum of modal gain. Thus, in this transition energy the \(\sigma -\) function emission peak appears. The situation described is equivalent to the conventional formulating of lasing threshold\(^3\), (the gain exceeds the losses). However, because of deviation from the quasiequilibrium the carrier distribution in some real structures obeys another law. As the system approach the threshold photon density becomes so high that the term in (5) that is responsible for interaction of electrons and holes with photons becomes dominating over others. It means that the external pumping slightly change carrier population. The mentioned effects are known as mode burning. In QD based system there were investigated spatial hole burning that is due to slowed carrier diffusion to the areas corresponding to optical wave loop\(^12\). This burning leads to appearing of multimode generation. Here, in the structure with strong inhomogeneous broadening we consider slowed carrier redistribution from QD levels with other transition energy.

In fig. 5 optically pumping experimental lasing spectra for A – type and B – type structures and calculated lasing spectra are presented. For these calculations radiative recombination time was chosen according to literature issues\(^30\) and capture parameter \(\sigma_n v_n\) was a fitting parameter.

![Fig5. Lasing spectra of structure with different active region. a) relatively narrow line in A – type structure agrees with calculated spectra with 10 ps escape and b) wide lasing line agrees with calculated one for 1 ns escape time.](image)

As it can be seen in fig. 5 escape time in structure of type B must be two order of magnitude longer than in A – type structure. The escape time in B – type structure is suggested to amount about 1 ns that is comparable with
recombination time, while the escape time for Al – type structure must amount about 10 ps that is comparable with time resolved data for shallow quantum dots. Although line broadening is so high this emission on the one hand will remain coherent and directional and on the other hand will not lead to threshold pumping power increase since the considered effects become apparent only above threshold or near the threshold (i.e. they just transform amplified spontaneous emission near the threshold).

6. CONCLUSIONS

Depending on growth regimes carrier localization depth and cattier state energy distance in the InGaN QDs varies significantly. In case of relatively shallow QDs carrier statistics is found to be almost quasiequilibrium at room temperature that follows from comparison of high sensitive PC spectra and light emission spectra. Emission spectra of these structures are also characterized by typical behavior or quasiequilibrium. However, QDs grown using growth interruptions have much deeper carrier localization and demonstrate strongly nonequilibrium properties that can not be described by the quasiequilibrium model. We solved numerically rate equation set that taking into account deviation of the quasiequilibrium and explaining the observed behavior. It is also possible to explain strongly widened lasing emission line in terms of this model. Slow carrier capture and escape times are the origin of the nonequilibrium and in the QDs with deep carrier localization these times are estimated to be two order of magnitude longer than in structure with relatively shallow QDs.

ACKNOWLEDGMENTS

Authors would gratefully acknowledge E. M. Arakcheeva for her experimental contribution to this work. The work was supported by grant RFBR and joint program with ITRI (Taiwan).

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