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Published in:
Journal of Applied Physics

DOI:
10.1063/1.4720584

Published: 01/01/2012

Document Version
Publisher's PDF, also known as Version of record

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Effects of lateral current injection in GaN multi-quantum well light-emitting diodes

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(Received 9 February 2012; accepted 16 April 2012; published online 31 May 2012)

In conventional multi-quantum well (MQW) LEDs, typically only one QW emits light due to a very nonuniform carrier distribution. We show by numerical simulations that by adopting a genuinely two-dimensional LED structure enabling lateral hole current injection into the QWs it becomes possible to achieve a more even carrier distribution potentially enabling smaller droop and uniform light emission from all the QWs in the MQW stack. We also show that the uneven emission may be explained with standard current transport models as quasi-Fermi losses between successive quantum wells. We demonstrate our findings by studying three different LED structures and comparing our results to published experimental results. © 2012 American Institute of Physics. [http://dx.doi.org/10.1063/1.4720584]

I. INTRODUCTION

One of the most studied effects related to LEDs made of InGaN quantum wells (QWs) is a strong efficiency droop at high current densities, which so far limits the use of LEDs in high-power solutions. One of the solutions proposed for reducing the efficiency droop is using multi-quantum well (MQW) active regions to reduce the carrier density in each QW and to move the peak efficiency to a higher current. However, in conventional MQW structures, typically only one of the QWs efficiently emits light due to a very nonuniform carrier distribution resulting largely from the current blocking by the barriers between the QWs.

Numerous computational studies about current transport in MQW LEDs have been published to date (see, e.g., Refs. 3–7). Most of these studies apply the drift-diffusion model which is commonly used to describe the steady-state operation of MQW LEDs. However, none of the references studies the quasi-Fermi level changes in the GaN barriers in more detail. As will be seen later in this report, these changes may explain why only one QW emits light, in addition to causing small increases in the forward voltages as shown experimentally, e.g., in Ref. 8.

Recently, Shi et al. proposed a LED structure they call the transverse-junction (TJ) light-emitting diode. This is an example of a structure that has a significant lateral current injection component to each QW from the side and thus cannot be described in detail by 1-dimensional models, which are used for modeling LEDs in most numerical works. To date, however, no numerical and theoretical studies have been published about lateral current injection and the current transport in genuinely two-dimensional LED structures.

Our work is intended to serve as a general theoretical reference on the effects of lateral current injection and current transport in genuinely 2-dimensional LED structures. We study numerically and analytically the semiconductor transport equations in 2-dimensional vertical- and transverse injection structures to better understand the origin of the transport-related losses and the effect they have on the performance of LEDs. We also present possible ways to improve current spreading and injection by comparing numerically the operation of the conventional thin-film flip-chip (TFFC) LED structure presented, e.g., in Ref. 11 and an intermediate form of the TFFC and TJ structures which we call the transverse-vertical junction (TVJ) LED (see Fig. 1). We also compare our results to those presented experimentally in Refs. 9 and 10 and show that the two-dimensional injection structures have several potential benefits in designing GaN LEDs.

This paper is organized as follows. In Sec. II, we shortly review the basic physical models for current transport in nitride semiconductors and present an analytic approximation for the changes of quasi-Fermi levels. In Sec. III, we present the simulated structures and the simulation results, and discuss the estimated efficiencies, band diagrams, and recombination profiles.

II. THEORY

The presented LED structures are studied by using a numerical transport model based on the drift-diffusion current equations and continuity equations for the carriers. The model consists of the conventional partial differential equations for the electrostatic potential \( \phi \) and the quasi-Fermi potentials \( \phi_n \) and \( \phi_p \) for electrons and holes, respectively,

\[
\nabla \cdot (-\varepsilon \nabla \phi + \mathbf{P}_{\text{tot}}) = q(p - n + N_d - N_a) \\
\n\nabla \cdot \mathbf{J}_n = -q\mu_n n \nabla \phi_n = qR \\
\n\n\nabla \cdot \mathbf{J}_p = -q\mu_p p \nabla \phi_p = -qR,
\]

where \( n \) is the density of electrons in the conduction band, \( p \) is the density of holes in the valence band, \( N_d \) is the density of ionized donors, \( N_a \) is the density of ionized acceptors, \( R \) is the recombination rate per unit volume, \( \mathbf{P}_{\text{tot}} \) is the total built-in polarization consisting of both the spontaneous and piezoelectric polarizations, \( \varepsilon \) is the permittivity, \( q \) is the elementary charge, and \( \mu_n \) and \( \mu_p \) are the constant electron and

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hole mobilities, respectively. Due to different scattering mechanisms, the mobilities could be generalized to be direction-dependent, but in this work we assume them to be constant in every direction. Quasi-Fermi potentials are related to quasi-Fermi levels as $-q\nabla \phi_{\text{qf}} = \nabla E_{\text{F},p}$, and together with the electrostatic potential they define the current transport and carrier distributions. Fermi-Dirac statistics is used in calculating the electron and hole concentrations. A corresponding model is presented, e.g., in Ref. 12 with also a good description of the quantum corrections that can be applied to the model and numerical implementation.

The boundary conditions are chosen so that at all the material interfaces, the perpendicular components of the electric displacement field and the electron and hole currents are conserved over the interfaces. The parallel components of the electric field and the quasi-Fermi potential derivatives are conserved as well. At the contacts, we use Dirichlet boundary conditions so that at the n-type contact $\phi = 0$, $\phi_n$ is fixed according to condition $n = N_i$, and $\phi_p$ is set to the same value as $\phi_n$. At the p-type contact $\phi = \Delta \phi$, where $\Delta \phi$ is the sum of the junction potential and the applied bias, $\phi_p$ is fixed according to condition $p = N_i$, and $\phi_n$ is set to the same value as $\phi_p$.

The recombination rate $R$ in Eq. (1) is modeled with the well-known parametrized formula $s$ for the radiative, Shockley–Read–Hall (SRH), and Auger recombination so that

$$R = \left( \frac{A}{n + p} + B + C(n + p) \right)(np - n_i^2),$$

where $A$, $B$, and $C$ are the coefficients for SRH, radiative, and Auger recombination, respectively, and $n_i$ is the intrinsic carrier concentration. In Eq. (2), it has been assumed that the SRH recombination rates are equal for electrons and holes and that the electron and hole densities in the impurity level responsible for SRH recombination are equal to $n_i$. It has also been assumed that the Auger coefficients are equal for electrons and holes. The photon recycling is accounted for representing the coefficient $B$ as $(\rho_{\text{esc}} + \rho_{\text{abs}})B_0$, where $\rho_{\text{esc}}$ is the photon escape probability, $\rho_{\text{abs}}$ is the probability for the photons to be absorbed outside the active region, and $B_0$ is the radiative recombination coefficient when no photon confinement or photon recycling takes place (i.e., when $\rho_{\text{esc}} + \rho_{\text{abs}} = 1$).

The total built-in polarization $P_{\text{tot}}$ of III-Nitrides is induced by the asymmetry of the wurtzite crystal structure (spontaneous polarization) and the strain of the crystal close to the material interfaces (piezoelectric polarization).

The piezoelectric polarization is oriented parallel or antiparallel to spontaneous polarization, and it is calculated as

$$P_{\text{pc}} = e_{33} \eta_1 + e_{31}(\eta_1 + \eta_2),$$

where $e_{ij}$ are the piezoelectric constants, $\eta_1$ is the strain along the direction of the [0001] axis, and $\eta_1$ and $\eta_2$ are the perpendicular strains, which are assumed to be equal. The piezoelectric constants for III-Nitrides are about ten times larger than those of traditional III-V compounds (see, e.g., Ref. 15), which makes also piezoelectric polarization an important part of III-Nitride current transport models. The piezoelectric polarization can be calculated for III-Nitride binaries compactly as a function of only the basal strain following:

$$P_{\text{pc}}^\text{AlN} = -1.808\eta_1 + 5.624\eta_1^2 \text{ for } \eta_1 < 0$$
$$P_{\text{pc}}^\text{AlN} = -1.808\eta_1 - 7.888\eta_1^2 \text{ for } \eta_1 > 0$$
$$P_{\text{pc}}^\text{GaN} = -0.918\eta_1 + 9.541\eta_1^2$$
$$P_{\text{pc}}^\text{GaN} = -1.373\eta_1 + 7.559\eta_1^2.$$

Finally, values for the piezoelectric polarization for ternary alloys can be calculated by linear interpolation of the values presented in Eq. (4). The total built-in polarization is then calculated as $P_{\text{tot}} = P_{\text{sp}} + P_{\text{pc}}$.

We define the various LED efficiency figures in the usual way. The external quantum efficiency (EQE) is defined as the number of extracted photons divided by the number of injected carriers. The wall-plug efficiency (or the overall efficiency) is given by the optical output power divided by the electrical input power. The internal quantum efficiency (IQE) is the number of radiative recombination events
divided by all the recombination events, and the injection efficiency (INJ) is the number of recombination events divided by the number of injected carriers.

A. Quasi-Fermi losses

Numerical solutions of Eq. (1) predict that the quasi-Fermi levels between successive QWs are not constant. More specifically, in structures where electron current flows into a potential well, the equations predict that the drop in the conduction band edge is accompanied by a drop in the quasi-Fermi level for electrons slightly before the material interface. Similar effect is also present for holes. This change in the quasi-Fermi level takes place in the barrier before the interface of the well and may increase the operating voltage. Furthermore, such behaviour is needed to explain why typically only one QW emits light. We call these changes quasi-Fermi losses for reasons that will become evident.

It is instructive to study the quasi-Fermi losses in the barrier layers near the material interfaces by solving the drift-diffusion current equations analytically assuming negligible recombination in the barriers. The following calculation is done for the electron current but similar results follow trivially for holes. The 1-dimensional drift-diffusion current for electrons is given by

$$ J = -q
\mu_e n \frac{d\phi_n}{dx}. $$

(5)

For an approximately triangular potential barrier, we may write the electron density using the Boltzmann approximation as

$$ n = n_0 \exp\left(\frac{-qE_x - q\Delta\phi_n}{k_BT}\right), $$

(6)

where $n_0$ is the electron density at $x = 0$, $E$ is the constant electric field, $k_B$ is the Boltzmann constant, $T$ is the temperature, and $\Delta\phi_n = \phi_n - \phi_M$, $\phi_M$ being the quasi-Fermi potential at $x = 0$. We can then solve Eq. (5) analytically for a constant current density $J$ and obtain

$$ q\Delta\phi_n = -k_BT \ln\left(\frac{J}{\mu_e n_0 E}\left[\exp\left(\frac{qE_x}{k_BT}\right) - 1\right] + 1\right). $$

(7)

Equation (7) has a singular point $x_s$ at

$$ x_s = \frac{k_BT}{qE} \ln\left(1 - \frac{q\mu_e n_0 E}{J}\right). $$

(8)

Equation (7) gives the quasi-Fermi level change when moving from one QW to the next as predicted by the drift-diffusion equations. For $x \ll x_s$, the change is small but increases strongly for $x \sim x_s$. This means that if an electron current density $J$ ($J < 0$) is to be carried over a potential barrier characterized by an electric field $E$, the barrier thickness needs to be significantly smaller than the critical thickness $x_s$.

Note that a similar prediction is also found for the special case of $E = 0$, which is typical of conventional nonpolar III-V semiconductors. Then

$$ q\Delta\phi_n = -k_BT \ln\left(\frac{xJ}{k_BT \mu_e n_0} + 1\right), $$

(9)

and the singular point is

$$ x_s = \frac{k_BT \mu_e n_0}{J}. $$

(10)

However, this limitation is less strict than the limitation for polar materials.

III. RESULTS AND DISCUSSION

The simulated LED structures shown in Fig. 1 consist of the conventional TFFC structure and two different TVJ structures. The h-TVJ structure enables direct lateral hole injection from the side and the e-TVJ structure enables direct lateral electron injection from the side. Because the mobility of holes is very low in contrast to electrons, the active region of the h-TVJ is narrower than the other structures in Fig. 1. Note that in addition to the side contacts of the TJ structure presented in Refs. 9 and 10, our TVJ structures include an n-GaN current spreading layer (CSL). This makes the current transport properties different in our structures.

The active regions of the simulated structures consist of five 2.5 nm thick QWs separated by 10 nm thick undoped GaN barriers. The last GaN barrier between the QWs and EBL is 20 nm thick, and the EBL thickness is 50 nm. The material parameters used in the simulations are summarized in Table I, and the equations are solved using the finite element method (FEM) with a damped Newton iteration scheme. The effective masses ($m_e^*, m_h^*$) and effective densities of states ($N_e$, $N_h$) shown in Table I but not explicitly presented in Refs. 9 and 10, our TVJ structures include an n-GaN current spreading layer (CSL). This makes the current transport properties different in our structures.

The active regions of the simulated structures consist of five 2.5 nm thick QWs separated by 10 nm thick undoped GaN barriers. The last GaN barrier between the QWs and EBL is 20 nm thick, and the EBL thickness is 50 nm. The material parameters used in the simulations are summarized in Table I, and the equations are solved using the finite element method (FEM) with a damped Newton iteration scheme. The effective masses ($m_e^*, m_h^*$) and effective densities of states ($N_e$, $N_h$) shown in Table I but not explicitly

<table>
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<tr>
<th>Property</th>
<th>GaN n-CSL/ barrier/p-CSL</th>
<th>In$<em>{0.17}$Ga$</em>{0.83}$N</th>
<th>Al$<em>{0.2}$Ga$</em>{0.8}$N</th>
<th>EBL</th>
<th>Unit</th>
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<td>$10^{25}$ m$^{-3}$</td>
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present in Eqs. (1)–(10) are used in the simulations through well established relations found in any textbook.

The theoretical values for polarization calculated from first principles are available in Refs. 16 and 17. However, most numerical studies use values that are approx. 50% of these theoretical values (see, e.g., Refs. 18–20). This choice is usually made to get a better agreement between simulations and experiment, and due to experimental evidence of significantly smaller polarization-induced surface charges than predicted theoretically.21,22 Due to these arguments, we use polarization values that are 50% of the theoretical calculations as shown in Table I.

Note that although the parameter values of Table I are widely used in the literature, there is still considerable uncertainty, e.g., in the values related to band offset ratios. We use the band offset ratio of $\frac{\Delta E_c}{\Delta E_v} = 50:50$ for all alloys in our simulations. Refs. 21 and 26 demonstrate experimental band offset ratios for the InGaN/GaN material system of $\frac{\Delta E_c}{\Delta E_v} = 58:42$ and $\frac{\Delta E_c}{\Delta E_v} = 55:45$, respectively. The band offset we are using effectively takes into account the elevated ground state of electrons in the QWs.

A. Structures with 5 blue-emitting QWs

Fig. 2 shows the band diagrams of the TFFC and TVJ LED structures composed of five InGaN QWs emitting in the blue wavelength range (~450 nm), intrinsic GaN barriers between the QWs, AlGaN EBL, and n- and p-type GaN CSLs. The diagrams are plotted along a vertical line reaching from the n-type CSL to the p-type CSL in the middle of the structures. The current density through all the LEDs is around 3 A/cm² in the figures to study the band diagram near the maximum efficiency of the h-TVJ.

The quasi-Fermi losses are significantly smaller in the TVJ LEDs than in the TFFC LED: in the TFFC LED of Fig. 2(a) both electron and hole quasi-Fermi levels drop monotonously in the barriers between the QWs, whereas in the h-TVJ structure of Fig. 2(b), both quasi-Fermi levels exhibit smaller drops and the hole quasi-Fermi level is not monotonous due to the lateral hole current through the side to the MQW. In the e-TVJ structure of Fig. 2(c), the quasi-Fermi level for electrons is essentially constant throughout the active region and only the quasi-Fermi level for holes exhibits drops.

The difference between the LED structures follows from the direct lateral current component in the TVJ LEDs, which facilitates the flow of carriers from the side into each quantum well. This is a fundamental difference in the structures that is expected to be always present, although the magnitude of the difference may depend on the details of the structure, the quality of the regrown lateral junction, and the values of the material parameters.

The radiative recombination rate through the active region of the three LEDs using the same ~3 A/cm² current density is shown in Fig. 3. It shows that the h-TVJ LED offers a better optical power balance between all the QWs than the TFFC and the e-TVJ structures. This is a result of the better spreading of carriers in the QWs due to the direct current component and is another fundamental difference between the TFFC and the TVJ. Again, however, the magnitude of the difference is greatly affected by the detailed structure and the material parameters. Further calculations show that the effective number of emitting QWs peaks at 1.05, 1.03, and 3.8 at low current densities and goes to 1.02, 1.02, and 2.5 at large current densities in the TFFC, e-TVJ, and h-TVJ, respectively.

FIG. 2. Band diagrams of the (a) TFFC structure, (b) h-TVJ structure, and (c) e-TVJ structure via a straight vertical line in Fig. 1 in the middle of the structures starting from the n-type CSL and ending in the EBL. The current density is 2.98 A/cm² in the TFFC LED, 3.00 A/cm² in the h-TVJ LED, and 2.94 A/cm² in the e-TVJ LED. The bias voltages are 3.64 V, 2.70 V, and 3.37 V, respectively. The inset in (a) shows a zoomed figure of the conduction band and electron quasi-Fermi level, demonstrating a significant quasi-Fermi loss occurring in the barrier before the material interface. The inset in (c) shows the hole quasi-Fermi loss occurring in the barrier between the EBL and the uppermost QW. In these models, this loss has a significant effect on the transport of holes.

FIG. 3. Radiative recombination rate along a straight vertical line in Fig. 1 in the middle of the structures starting from the n-type CSL and ending in the EBL. The curves for different structures have been shifted relative to each other to make the figure easier to read. The current density is 2.98 A/cm² in the TFFC LED, 3.00 A/cm² in the h-TVJ LED, and 2.94 A/cm² in the e-TVJ LED. The bias voltages are 3.64 V, 2.70 V, and 3.37 V, respectively.

FIG. 4. Current-voltage characteristics of the TFFC and TVJ LEDs.
The current-voltage characteristics of the LEDs are shown in Fig. 4. The operating voltage for $J = 1 \text{A/cm}^2$ of the h-TVJ LED in the simulated structure is approximately 1 V below the corresponding operating voltage of the TFFC LED, due to the lower quasi-Fermi losses and more efficient carrier spreading. The large quasi-Fermi losses and the accompanying large operation voltage are caused mainly by the polarization-induced potential barriers especially in the EBL and the deep quantum wells. Reducing either the number of QWs or the height of the polarization-induced potential barriers reduces the operating voltage of all the structures.

The difference in the operating voltage may be reduced or lost if the growth process required in fabrication of the TVJ structures deteriorates the crystal quality near the transverse junction and causes a poor mobility, enhanced nonradiative recombination or additional potential barriers near the transverse junction. This, in addition to the differences in the CSL, is expected to explain why the reduced operating voltage was not observed in Ref. 10. For comparison, we have also simulated the operation of a structure which resembles that of the TJ structure of Ref. 10, i.e., which has undoped CSL below the MQW and direct electron injection. Otherwise the structure parameters are similar with the e-TVJ of Fig. 1. The current-voltage characteristics of the TFFC LED, the depicted TJ LED (TJ\text{non-degraded}) and the TJ LED with an additional potential barrier between the n-type contact and the MQW due to the regrowth process (TJ\text{degraded}) are repeated in a linear scale in Fig. 5 to compare with the results of Refs. 9 and 10. The TJ\text{non-degraded} has a higher current than the TFFC at low voltages due to the direct electron injection. At voltages greater than approx. 3.9 V, the low conductivity of the undoped CSL and the MQW cause the current to remain notably lower in the TJ\text{non-degraded} than in the TFFC. These factors also affect the operation of TJ\text{degraded}, where in addition to previous arguments, the potential barrier between the n-type contact and the MQW cause the current to stay lower than in the TFFC at all voltages.

Resistive losses and quasi-Fermi level losses of all the LEDs are compared in Fig. 6 as a function of the current density. The curve denoted as $\Delta \phi$ shows the onset of resistive losses along the n-type current-spreading layer from the n-contact to the end of the CSL ($\Delta \phi_{n}\text{-}\text{c}$), and the p-type quasi-Fermi level from the p-type contact to the uppermost QW ($\Delta \phi_{p}\text{-}\text{c}$). The TFFCstructure is only 10 $\mu$m wide and correspondingly $\Delta \phi$ is very small. The curves denoted as $\delta \phi_{n}$ and $\delta \phi_{p}$ show the change in the electron quasi-Fermi level from the n-type contact to the central QW and the hole quasi-Fermi level from the p-type contact to the uppermost QW, respectively. The electron quasi-Fermi level is significantly greater in the TFFC structure than in the TVJ structures throughout the simulated current density range, as also seen in the band diagrams. The hole quasi-Fermi loss of the TFFC and e-TVJ structures is of the same magnitude, but for h-TVJ it is much lower due to the direct hole injection.

The relevant efficiency figures of all the LEDs are shown in Fig. 7. IQE (Fig. 7(a)) only account for the recombination in the QWs, while EQE (Fig. 7(b)) also accounts for the leakage current and the (constant) extraction efficiency. Due to the better spreading of carriers to the QWs in the h-TVJ, the droop of the h-TVJ takes place at a higher current than in the other structures. In addition, the h-TVJ has a higher maximum quantum efficiency due to a better carrier distribution.

The effect of the leakage current is seen in the injection efficiency (Fig. 7(c)), which decreases slowly as a function of the current density in spite of using an EBL. At low and moderate currents, the injection efficiency is slightly lower in the TFFC and e-TVJ LEDs because the transport loss for holes shown in the inset of Fig. 2(c) causes an unnecessarily high voltage which increases electron leakage. At currents above 100 $\text{A/cm}^2$, the injection efficiency of the h-TVJ structure drops rapidly because of the pn junction in the regrown region (see Fig. 1).

The wall-plug efficiency of the h-TVJ LED (Fig. 7(d)) stays notably higher than the wall-plug efficiency of the TFFC LED for most of the simulated current density range. This is due to notably smaller quasi-Fermi loss and the corresponding difference in the operating voltages seen in Fig. 4, which makes the electrical input power needed to excite the TVJ much lower than that for the TFFC LED. Also the higher IQE and injection efficiency of the h-TVJ improve its overall efficiency at low and moderate currents.
B. Structures without EBL

The motivation for using electron-blocking layers in LEDs is to prevent electrons from leaking from the active region into the p-side of the structure. In the structures analyzed above, we used Al$_{0.2}$Ga$_{0.8}$N as the EBL. In spite of the EBL, the injection efficiency in the TFFC and e-TVJ structures is less than 1 and decreases throughout the useful current density range, $J_{\text{inj}} \approx 10^3/T_1$. Using AlGaN EBLs with too high Al content is known to decrease the quantum efficiency by increasing the harmful Auger combination and also to block hole transport to the active region. To study the effects of EBL, we have simulated structures in which the EBL is replaced by an equally thick p-type GaN layer. Otherwise the structures simulated in this Subsection are equivalent to those in Subsection III A with 5 blue-emitting QWs.

The band diagrams of the LEDs without the EBL are shown in Fig. 8. The large hole quasi-Fermi loss that was visible in the inset of Fig. 2(c) has vanished, indicating a better hole injection. The quasi-Fermi level for electrons still suffers significantly lower losses in the e-TVJ and h-TVJ structures than in the TFFC structure, and the quasi-Fermi level for holes suffers lower losses in the h-TVJ than in the other simulated structures.

The radiative recombination rate through the active region of the LEDs without the EBL is shown in Fig. 9. The large hole quasi-Fermi loss that was visible in the inset of Fig. 2(c) has vanished, indicating a better hole injection. The quasi-Fermi level for electrons still suffers significantly lower losses in the e-TVJ and h-TVJ structures than in the TFFC structure, and the quasi-Fermi level for holes suffers lower losses in the h-TVJ than in the other simulated structures.

The radiative recombination rate through the active region of the LEDs without EBL is shown in Fig. 9. Also in this case, the h-TVJ structure has a better carrier distribution among the QWs in contrast to TFFC and e-TVJ structures where only the QW next to the p-type region emits light. Further calculations show that the effective number of emitting QWs peaks at 1.09, 1.06, and 3.8 at low current densities and goes to 1.02, 1.02, and 2.5 at large current densities in the TFFC, e-TVJ, and h-TVJ, respectively.

The current-voltage curves for EBL-free structures are shown in Fig. 10. The operating voltage difference has diminished, mainly due to better hole injection. However, the operating voltage of both TVJ LEDs is still notably lower than in the TFFC.

The simulated internal quantum efficiency, external quantum efficiency, injection efficiency, and wall-plug efficiency are shown in Fig. 11. It can be seen that the IQE (Fig. 11(a)) and EQE (Fig. 11(b)) are not essentially changed as the EBL is left out. The quantum efficiency of the h-TVJ peaks at a higher current than in the TFFC and e-TVJ structures due to better carrier spreading.

The injection efficiency (Fig. 11(c)), on the other hand, is now nearly 100% instead of the 90%–100% for structures with AlGaN EBL. As a consequence of the improved injection efficiency, the wall-plug efficiency (Fig. 11(d)) of the
TFFC and e-TVJ structures has also increased. Our results suggest that in the TFFC and e-TVJ structures, the Al0.2Ga0.8N EBL indeed blocks hole current into the active region in the sense that a higher voltage is required to overcome the valence band quasi-Fermi losses and to reach the desired current density. This, however, has no direct effect on the injection efficiency. Instead, the large operating voltage itself increases the electron concentration in the p-type material and thereby enables higher leakage.

The wall-plug efficiency (Fig. 11(d)) is higher in the h-TVJ than in the other structures due to the lower turnon voltage of Fig. 10 and the corresponding lower input power needed to excite the LED. The wall-plug efficiency of the h-TVJ also peaks at a higher current.

C. Analytic estimation of quasi-Fermi losses

According to the numerical results, the quasi-Fermi losses play a significant role in determining the operating voltage and carrier distribution of LEDs. In order to better understand the limitations of geometry on the current transport, it is useful to study the losses in analytic form. Fig. 12 shows the conduction band edge and quasi-Fermi level calculated using Eq. (7) with a linear electrostatic potential and selected current density values. The figure shows that the analytical model predicts very sharp changes in the quasi-Fermi level. The singular points are clearly identified in the figure as the points where the quasi-Fermi level drops abruptly. Most importantly, the figure shows that to obtain small quasi-Fermi losses with a given electric field, the barrier thickness must be small and the maximum thickness depends on the desired current density.

To compare the analytic model of the Fermi losses to simulation data, we have to estimate the polarization-induced electric fields in the MQW region. A very simple approximation can be done, e.g., by following Ref. 28, where the electric fields are calculated assuming the electrostatic potentials to be approximately equal at both ends of the structure (corresponding to a bias voltage equal to the internal potential difference of the LED). However, in this work, we compare the analytic model to simulation data by taking the values for the electric field and current density from the numerical results.

Fig. 13 compares Fermi level losses given by the numerical and analytical solutions for a structure with one 2.5 nm thick In0.15Ga0.85N QW sandwiched between 10 nm thick GaN barriers. Fig. 13(a) shows the simulated band diagram, and Fig. 13(b) shows the Fermi level loss calculated by the analytical solution with values for n0, electric field and current density taken from the simulated solution. The current density in the left-side barrier is 0.27 A/cm2, and n0 = 2.5 × 10^{19} 1/m^3. The numerical and analytic models give qualitatively similar results.

Fig. 14 shows the maximum barrier width as a function of the electric field in the barrier for different current density values assuming n0 = 2.5 × 10^{19} 1/m^3. The maximum barrier width decreases as the electric field or current increases, as mentioned earlier.

The quasi-Fermi loss shows up in most numerical simulations of MQW LEDs. In the conventional drift-diffusion approach, it occurs slightly before the material interface, whereas, e.g., in the thermionic emission theory, the quasi-Fermi level itself is considered discontinuous over the interface. In qualitative terms, however, both models predict...
In general, however, the drift-diffusion model has been shown to correctly predict the qualitative and even quantitative behaviour of III-N MQW LEDs especially at medium-high current densities (see Ref. 29), and the largest source of error in using the drift-diffusion model is expected to be the uncertainty in the material parameters.

For example, the values for the spontaneous and piezoelectric polarization have been widely discussed and it has been proposed that the correct values are significantly smaller than the theoretical estimates. Based on this, many computational studies of III-Nitride LEDs, including this, use polarization values that are about 50% of the theoretical estimates.

Even though we have mainly concentrated on the current spreading in this paper, the results are strongly related to the efficiency droop phenomenon observed in III-Nitride LEDs, because the uniform carrier distribution throughout the MQW structure reduces the droop. Furthermore, our simulations that account for nonradiative SRH and Auger recombination as well as current transport, suggest that increased Auger recombination is the principal reason for the droop.

IV. CONCLUSIONS

We compared different 2-dimensional LED structures and geometries and showed that departing from the conventional essentially 1-dimensional LED structures and models may dramatically facilitate current transport, improve the wall-plug efficiency and distribute the carriers more evenly in the active regions of MQW structures, thereby reducing the droop. In particular, the lateral current transport in the TVJ structure allows for lower quasi-Fermi losses and thereby better wall-plug efficiencies and more uniform carrier density compared to conventional 1-dimensional MQW structures.

The TVJ structure studied in this paper represents only one example of LED structures that make use of truly two-dimensional current transport. However, the favorable comparison of this structure to the conventional structures shows the importance of further research of these structures and the potential benefits of other simple modifications to conventional structures.

In addition to numerical simulations, we derived an analytical model for predicting the quasi-Fermi losses in the active region of LEDs based on the semiconductor current equations and discussed the manifestation of the quasi-Fermi loss in real structures. Our model explains the basic behaviour of the quasi-Fermi levels in strained MQW regions with high internal polarization fields but a more accurate treatment based on more sophisticated current transport models is needed to quantitatively verify the behaviour of the quasi-Fermi levels inside a MQW stack and to proceed in accurate numerical modeling of nanoscale LEDs.

ACKNOWLEDGMENTS

The research has been in part supported by the Academy of Finland and the Multidisciplinary Institute of Digitalisation and Energy program (MIDE) of the Aalto University.


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