Theoretical study of current overflow in GaN based light emitters with superlattice cladding layers

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We investigate the effect of the short-period superlattice cladding layer on electron current overflow in nitride light emitters. The classical drift-diffusion current flow and quantum tunneling transport through the miniband are considered. We show that the drift-diffusion electron current in the *p*-type superlattice cladding layer is drastically reduced by the presence of the intrinsic built-in electric fields. Based on this finding, we propose a design of the electron blocking layer which should considerably lower the electron current overflow in nitride light emitters. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2212127]

Due to low efficiency of *p*-type doping in nitride alloys, the performance of nitride light emitters is strongly affected by electron current overflow. When substantial part of the electron flux does not recombine in the active region of the device but penetrates into the *p*-type waveguide or cladding layers, the efficiency of light emission decreases and the operation temperature increases. For lasers, it automatically leads to increase of the threshold current and deterioration of the operation lifetime. To prevent penetration of electrons into *p*-type layers of the lasers or light emitting diodes, a high aluminum content AlGaN layer, called electron blocking layer (EBL), is conventionally used.[1–4] Detailed analysis of reducing the electron current overflow by EBL has been recently performed.[5]

In addition to the EBL, short-period GaN/AlGaN superlattices (SLs) are the other specific components of the nitride laser structures. It turns out that the usage of the SLs, instead of the bulk AlGaN layers, as the cladding layers in nitride laser diodes leads to (i) better crystal quality of the laser structures,[6] and (ii) increase of the hole concentration due to valence band bending in the *p*-type SL, caused by the spontaneous and piezoelectric polarizations.[7]

In this work, we examine the effect of the short-period SL cladding layers on electron current overflow in nitride light emitters. We consider the classical drift-diffusion current flow and quantum tunneling transport through the miniband. We show that the drift-diffusion electron current in the *p*-type SL cladding layer is drastically reduced by the presence of the built-in electric fields. Finally, we propose a construction of the EBL which should considerably lower the electron current overflow in nitride light emitters.

We start by calculating conduction and valence band profiles, distribution of quasi-Fermi levels, and electron and hole currents in a laser structure using classical drift-diffusion model. As an exemplary structure, we have taken the high power blue laser diode from Ref. 3. In this structure, both cladding layers are formed by (2.5 nm/2.5 nm) $GaN/Al_{0.16}Ga_{0.84}N$ SLs.[3] The numerical computations have been performed using the SILENSE package,[8] with parameters taken from Refs. 9 and 10. In Fig. 1, we show the band profiles and the quasi-Fermi levels for electrons and holes obtained for our laser structure at the external voltage U_{ext} =3.3 V. Moving from left to right, one can clearly recognize a part of the *n*-type SL, the *n*-type optical guiding layer, the multi-quantum-well active region, the EBL, the *p*-type optical guiding layer, and a part of the *p*-type SL. For the analysis of the electron current overflow, the change of the electron quasi-Fermi level E_{Fn} in *p*-type layers is important. From Fig. 1, we observe that E_{Fn} drops significantly behind the EBL, which is the well known effect of the blocking of electron current by the EBL. Interestingly, one can see that in the *p*-type SL, E_{Fn} decreases rapidly which suggests strong reduction of electron flux by the *p*-type SL. Similar behavior is observed for holes in the *n*-type SL. This effect is presented more pronouncedly in Fig. 2, where we plot the drift-diffusion electron current density $j_{e(dd)}$. The solid line corresponds to $j_{e(dd)}$ calculated for our laser structure with SLs in both claddings. The dashed line represents $j_{e(dd)}$ obtained for the laser structure in which both SLs have been replaced by bulk $Al_{0.08}Ga_{0.92}N$ layers with average Al content. Comparing both curves, one can realize that the usage of the SL as

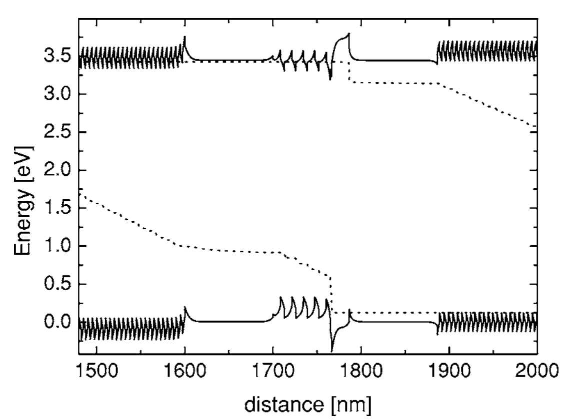

FIG. 1. The conduction and valence band profiles (solid lines) and the quasi-Fermi levels for electrons and holes (dotted lines) obtained for the considered laser structure, for U_{ext}=3.3 V.

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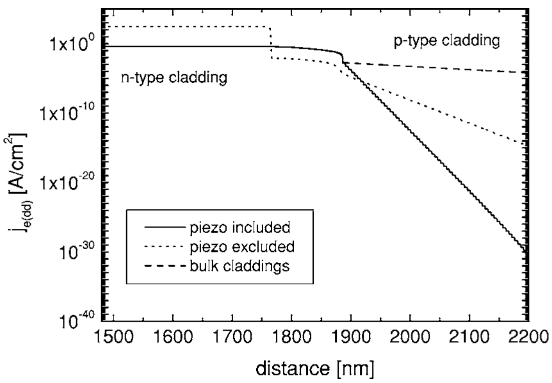

FIG. 2. The distributions of $j_{e(\mathrm{dd})}$, obtained for the laser structure (i) with SLs cladding layers (solid line), (ii) with bulk $Al_{0.08}Ga_{0.92}N$ cladding layers (dashed line), and (iii) with SLs cladding layers but when the spontaneous and piezoelectric polarizations are neglected in the calculations (dotted line).

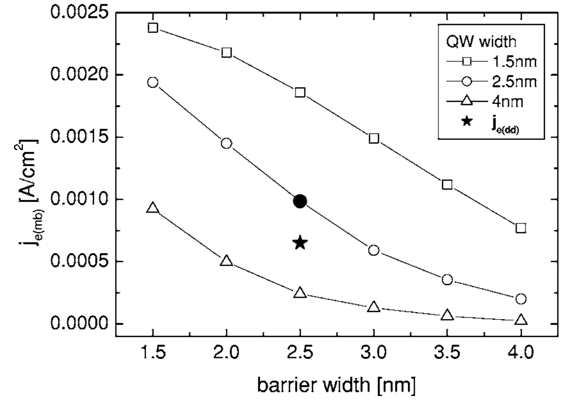

FIG. 4. The values of $j_{e(\mathrm{mb})}$, calculated for the $GaN/Al_{0.16}Ga_{0.84}N$ SLs with various L_{qw} and L_{br}. The solid dot and solid star represent $j_{e(\mathrm{mb})}$ and $j_{e(\mathrm{dd})}$ obtained for the SLs used in the considered laser structure.

the p-cladding layer dramatically reduces the electron current overflow in the device. Interestingly, this effect is closely combined with the presence of the built-in electric field in the GaN/AlGaN SL caused by piezoelectric and spontaneous polarizations. To illustrate this point, we show $j_{e(\mathrm{dd})}$ (dotted line in Fig. 2) calculated in our laser structure with SLs but neglecting both spontaneous and piezoelectric polarizations. In this case, the reduction of classical electron current in the p-type SL is much smaller in comparison with the result obtained when the built-in electric fields have been taken into account.

In order to complete the analysis of electron current overflow, we have to consider the transport through the miniband formed in the p-type SL. The task can be divided into two steps. In the first step, we compute the miniband structure solving one-band effective mass equation with periodic boundary conditions for the wave functions $\psi(0)=\psi(L)e^{ik_z z}$, where k_z is the electron wave number and L is a period of the SL. The conduction band offset and the built-in electric fields are taken into account as described in Ref. 11. Numerical computations have been performed using the finite element method.[12] In Fig. 3, we show the first miniband energy dispersions $E_m(k_z)$ for three $GaN/Al_{0.16}Ga_{0.84}N$ SLs with identical widths of barriers L_{br}, and wells, L_{qw}. The obtained widths of the miniband (156, 34, and 3 meV for the SLs with

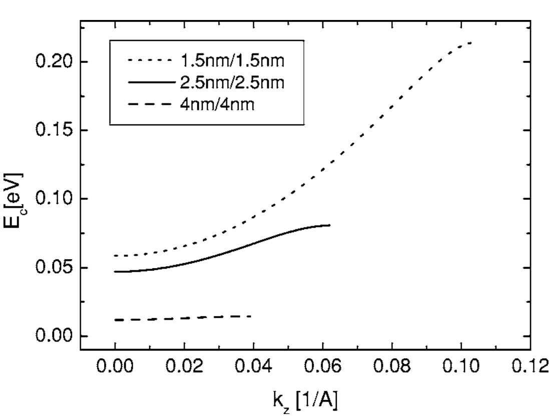

FIG. 3. The first miniband energy dispersions for three $GaN/Al_{0.16}Ga_{0.84}N$ SLs with $L_{\mathrm{br}}=L_{\mathrm{qw}}=1.5$, 2.5, and 4 nm, respectively.

$L_{\mathrm{br}}=L_{\mathrm{qw}}=1.5$, 2.5, and 4 nm, respectively) are in good agreement with previous calculations.[13,14]

In the second step, we calculate the miniband electron current density $j_{e(\mathrm{mb})}$ using standard semiclassical approach based on the Boltzmann transport equation.[15] Using the relaxation time approximation, one can derive the following formula for $j_{e(\mathrm{mb})}$:

$$j_{e(\mathrm{mb})}=\frac{e^2\tau F m_e k_B T}{2\pi^2\hbar^4}\int_{-\pi/L}^{\pi/L}\log(1+\exp\{[E_{\mathrm{Fn}} - E_m(k_z)]/k_BT\})\frac{d^2E_m(k_z)}{dk_z^2}dk_z, \quad (1)$$

where e is the elementary charge, τ is the average scattering time, F is the average electric field in the SL, $m_e=0.2m_0$ is the average in-plane effective mass of electrons,[9] k_B is the Boltzmann constant, and T is the temperature. From the electron mobility in p-type GaN (30 cm^2/Vs),[16] we estimate $\tau=3.41\times10^{-15}$ s. The values of $F=5.8\times10^5$ V/m and $E_{\mathrm{Fn}}=3.035$ eV are determined from the results obtained from the drift-diffusion model for our laser structure, at $U_{\mathrm{ext}}=3.3$ V. In Fig. 4, we show the values of $j_{e(\mathrm{mb})}$ calculated for SLs with different L_{br} and L_{qw}. Interestingly, the value of $j_{e(\mathrm{mb})}$ for the SL used in our laser structure (solid dot) is comparable to the value of $j_{e(\mathrm{dd})}$ (solid star) taken for the first period of the p-type SL. This finding suggests that the overflow current in our laser structure is determined by both drift-diffusion and miniband transports. From Fig. 4, it is clear that to suppress $j_{e(mb)}$, one has to increase L_{br} or L_{qw}. Particularly, for SL with $L_{\mathrm{br}}=L_{\mathrm{qw}}=4$ nm, the value of $j_{e(\mathrm{mb})}$ decreases almost two orders of magnitude, in comparison with the SL with $L_{\mathrm{br}}=L_{\mathrm{qw}}=2.5$ nm.

Finally, we discuss the properties of the EBL. Very recently, Lee *et al.* have reported a design of the violet laser diode, in which the EBL was formed by a sequence of thin AlGaN quantum barriers, separated by GaN quantum wells (QWs) with different widths.[17] They have found that the laser possesses lower threshold current and higher quantum efficiency in comparison with conventional laser structures with the bulk EBL. The improvement of the laser performance has been attributed to suppression of the electron cur-

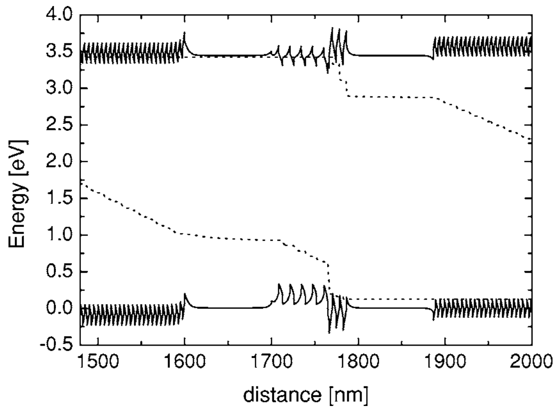

FIG. 5. The conduction and valence band profiles (solid lines) and the quasi-Fermi levels for electrons and holes (dotted lines) obtained for the laser structure with the SL-EBL, for $U_{ext}=3.3$ V.

rent overflow, but any quantitative analysis has not been done. We would like to explore further this idea of the multi-quantum-barrier EBL. We propose to use the EBL in the form of a few periods of GaN/AlGaN SL (the SL-EBL). Particularly, let us consider the laser structure, in which the 20-nm-thick $Al_{0.22}Ga_{0.78}N$ EBL has been replaced by the SL-EBL built from three $Al_{0.22}Ga_{0.78}N$ barriers ($L_{br}=4$ nm) and two GaN QWs ($L_{qw}=4$ nm). In Fig. 5, we show the band profiles and quasi-Fermi levels obtained for the laser structure, at $U_{ext}=3.3$ V. One can see that E_{Fn} drops drastically behind the SL-EBL. This drop is much larger than for the case of the laser structure with the bulk EBL (see Fig. 1). One can claim then that the usage of SL-EBL improves reduction of the classical overflow current. The direct comparison of $j_{e(dd)}$ behind the SL-EBL [$j_{e(dd)}=8.9\times10^{-6}$ A/cm^2] and behind the bulk EBL [$j_{e(dd)}=0.28$ A/cm^2] shows that the difference in $j_{e(dd)}$ is about five orders of magnitude. However, considering the overflow current in the structure with the SL-EBL, one has to take into account the quantum tunneling effect. For this purpose, we calculate the electron tunneling current flowing from one well to the other inside the SL-EBL. The following formula reads

$$j_{e(t)} = \frac{e|H_{1,2}|^2}{\hbar}\frac{2(\hbar/\tau)}{(eFL)^2+(\hbar/\tau)^2}\left[n_{2D}(1) - n_{2D}(2)\exp\left(-\frac{eFd}{k_BT}\right)\right], \quad (2)$$

where $n_{2D}(i)=m_e k_B T/(\pi\hbar^2)\log(1+\exp[[E_{Fn}(i)-E_q(i)]/(k_BT)])$, $i=1,2$ are the average two-dimensional electron densities in the first and the second wells of the SL-EBL, $E_q(i), i=1,2$ are the first energy levels in both quantum wells, and $|H_{1,2}|$ is the tunnel matrix element.[15] We take $E_{Fn}(1)=3.3296$ eV, $E_{Fn}(2)=3.1108$ eV, $F=4.05\times10^6$ V/m, $E_q(1)=3.5144$ eV, $E_q(2)=3.482$ eV, and $|H_{1,2}|=0.9$ meV from the results obtained using of the drift-diffusion model ($U_{ext}=3.3$ V) and the effective mass equation. Using the above values, we get $j_{e(t)}=3.6\times10^{-6}$ A/cm^2, which is similar to the value $j_{e(dd)}$ obtained for the structure with the SL-EBL. Therefore, taking into account both $j_{e(dd)}$ and $j_{e(t)}$, one predicts that the usage of the SL-EBL instead of the bulk EBL should result in large (four orders of magnitude) reduction of the electron current overflow.

In conclusion, we have examined the electron current overflow in nitride laser structure with SL claddings, using the drift-diffusion and miniband transport models. We have shown that the electron drift-diffusion current is strongly reduced in the p-type SL by the presence of the built-in electric fields. The electron miniband current is significant in commonly used SLs (with $L_{br}=L_{qw}=2.5$ nm), but it may be considerably reduced by increase of the L_{qw} and L_{br}. Finally, we have proposed the EBL structure in the form of 2.5 periods of the $GaN/Al_{0.22}Ga_{0.78}N$ SL with $L_{br}=L_{qw}=4$ nm, which should drastically reduce the electron current overflow in the blue-violet lasers.

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