Suppression of electron leakage by inserting a thin undoped InGaN layer prior to electron blocking layer in InGaN-based blue-violet laser diodes

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Abstract: InGaN-based blue-violet laser diodes (LDs) suffer from electron leakage into the p-type regions, which could be only partially alleviated by employing the electron blocking layer (EBL). Here, a thin undoped InGaN interlayer prior to EBL is proposed to create an additional forbidden energy range above the natural conduction band edge, which further suppresses the electron leakage and thus improve the characteristics of LDs. Numerical device simulations reveal that when the proper composition and thickness of InGaN interlayer are chosen, the electron leakage could be efficiently eliminated without inducing any severe accumulation of electrons at the interlayer, resulting in a maximum output power of the device.

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1. Introduction

InGaN-based laser diodes (LDs) have obtained much attention in the last decades due to their wide applications in various areas such as full-color displays, high-density optical data storage, and chemical sensors [1,2]. However, in the conventional blue-violet InGaN-based laser diodes, considerable leakage of electrons always exists because of the weak confinement capability of electrons within the shallow quantum wells. As a result, the poor hole injection efficiency due to heavy effective mass and low mobility will be further deteriorated because of the recombination of carriers in the p-type region. A great number of proposals can be found in literature on how to reduce the electron leakage, in particular, by design optimization of the AlGaN electron blocking layer (EBL), which is inserted coherently to the active region to limit electron leakage into the p-doped side. Among these publications, AlGaN/GaN multi-quantum-barriers (MQBs) have been widely employed to replace the conventional AlGaN single EBL [3–5]. Due to the band bending caused by its alternating-composition structure, the conduction band barrier against electron overflow is increased, while the energy barrier for hole injection is almost maintained. Another approach to enhance the electron confinement and increase hole injection into the active region relates to the introduction of polarization-matched AlInGaN quaternary [6–8]. By using the AlInGaN EBL with proper aluminum and indium compositions, the built-in charge density at the interface between the last quantum barrier (QB) layer and the AlInGaN EBL could be reduced to prevent from forming an electron accumulation layer. Moreover, a tapered AlGaN EBL with step-graded aluminum composition is also proposed to reduce the electron leakage and facilitate the tunneling of low energy holes into the active region [9,10]. However, the substitutive AlGaN layers must be p-doped to lower the electron quasi Fermi level, which may accelerate the magnesium diffusion into the MQW active region.

In this work, a rather simple but effective approach by inserting only a thin undoped InGaN interlayer prior to the EBL is proposed in the new structure and expected to improve the device performance of InGaN-based blue-violet LD. Noted that the indium composition needed in this interlayer is very small, i.e., no more than 5%, it is highly practical to implement such new structure in the material growth. Using numerical simulation, the electrical and optical characteristics of both new and reference LD structures are calculated and analyzed. It is found that by additionally inserting a thin undoped InGaN layer, the barrier height between the last QB layer and EBL is increased because of the enhanced EBL conduction band offset ($\Delta E_c$). As a result, the electron leakage current is reduced dramatically, and the threshold current density and slope efficiency for new LD are improved.
2. Experiments

There are two different structures in our simulation as shown in Fig. 1. The reference structure (denoted as Ref. LD) is composed of a 3 um Si-doped n-type GaN layer, a 0.1 um Si-doped n-type In_{0.05}Ga_{0.95}N layer, a 0.5 um Si-doped n-type Al_{0.16}Ga_{0.84}N/GaN superlattice (SL) lower cladding layer, a 0.09 um Si-doped n-type GaN lower waveguide layer, the active region of 3-periods 3.5 nm-In_{0.15}Ga_{0.85}N/7 nm-GaN MQW but the thickness of the first and last QB layers is 10 nm, a 0.02 um Mg-doped p-type Al_{0.2}Ga_{0.8}N EBL, a 0.5 um Mg-doped p-type Al_{0.16}Ga_{0.84}N/GaN SL upper cladding layer, and 0.3 um Mg-doped p-type GaN layer. In the new structure (denoted as New LD), an additional 5 nm undoped In_{0.05}Ga_{0.95}N is inserted prior to EBL and the thickness of last GaN QB layer is reduced to 5 nm. Other part of the structure keeps the same as the reference LD. The cavity length of both LDs is 500 um and the width of ridge is 4 um. The reflectivity of both end mirrors is set as 0.5.

3. Results and discussion

The self-consistent Schrödinger-Poisson equation was employed to calculate the energy band profile with a commercial software package LASTIP [11]. In the calculation, built-in interface charges due to spontaneous and piezoelectric polarization were calculated according to the parameters given by Bernardini et al. [12]. The polarization factor due to partial compensation of the built-in polarization by charged defects was set to be 25%, and the band offset ratio ($\Delta E_c/\Delta E_g$) was 0.67.
Fig. 2. Vertical electron energy band diagram near the active region of the (a) reference and (b) new structure LDs at 100 mA. The dashed lines mark the quasi Fermi levels $E_{fn}$ and $E_{fp}$, and $\Delta E_n$ and $\Delta E_p$ are the EBL energy barrier for electrons and holes, respectively.

Figure 2 plots the energy band diagram of the reference and new structure LDs. The presence of interface polarization charges, ionized impurities, free carriers, and applied bias leads to strong deviations from the ideal rectangular shape of the band edge profiles for both LDs. In addition, there is an evident potential dip at the interface between the last QB layer and EBL, which is located beneath the electron quasi Fermi level and thus enhance the electron density on the left-hand side (LHS) of the EBL. It is noted that in new LD with an additional thin $\text{In}_{0.05}\text{Ga}_{0.95}\text{N}$ layer prior to EBL, the built-in conduction band offset ($\Delta E_c$) of EBL is increased and the quasi Fermi level is pulled down as compared with that of reference LD. As a result, the conduction band barrier height for electron is now $\Delta E_n = 297$ meV, much higher than the barrier height in the reference LD ($\Delta E_n = 206$ meV). Since there is no any change in the right-hand side of the EBL, the energy barrier for hole injection is almost identical ($\Delta E_p = 166$ meV). One also can see that the conduction band quasi Fermi level in the p-type regions of new LD is much lower than the bottom edge of conduction band in comparison with that of the reference LD, which indicates that there is a much smaller electron leakage current in the new LD.

Fig. 3. Vertical electron current density versus position in reference and new LDs at 100 mA.
Figure 3 shows the vertical electron current density profiles surrounding the active region of the reference and new LDs at 100 mA. The electrons are injected from n-type layers into the active region and recombine with holes in quantum wells, resulting a reduced electron current density in the profile of quantum wells [13]. It is also noted that the reduction of electron current density becomes larger from n-side to p-side since more carriers distribute and recombine in the quantum well near the p-side of LD. For reference LD, the reduction of electron current density is smaller than that of new LD, especially in the last quantum well near p-side, illustrating that more carriers are confined and recombined in quantum wells near the p-side of new LD. For the reference LD, outside the active region the electron leakage current is much severer, i.e., 18% of the injected electrons leak into the p-side, while such leakage disappears almost completely after the insertion of a 5 nm thick In$_{0.05}$Ga$_{0.95}$N layer. It is known that the electron leakage plays a negative role for the optical performance of III-nitride LD since it will result in the carrier loss by the recombination of leaked electrons and holes in the p-type region, and thus increase the threshold current density [14,15].

The electron and hole concentrations of the reference and new LDs at 100 mA are shown in Fig. 4. It is found that the carrier concentration in quantum wells close to the p-side of new LD is higher than that of reference LD, which should be attributed to the reduction of electron leakage into p-side layers. In addition, Fig. 4(a) shows an evident accumulation of electrons on the LHS of EBL for both LDs, and it becomes severer when the thin InGaN layer is added. Actually, the inserted InGaN layer would act as an unintentional shallow quantum well to capture more carriers and induce more non-stimulated recombinations, thus may deteriorate the LD performance. It is also noted that an increased indium composition would exacerbate such a trend (shown in Fig. 5). On the other hand, inserting InGaN layer with high indium composition will increase the built-in conduction band offset ($\Delta E_c$) of EBL and thus reduce the electron leakage. Therefore, it is significant to choose a proper indium composition for the inserted thin InGaN layer as a compromise.

In fact, in our simulation, it is found that under high injection condition it is more important to reduce the electron leakage than to alleviate the electron accumulation. This is due to the fact that when the injection current is very large, the electron loss induced by accumulation will reach a saturation since there will be no sufficient holes to recombine with these accumulated electrons in the region of inserted InGaN layer, as shown in Fig. 4(b). However, the electron leakage induced by overflow always increases as the injection current increases, and may even become a determinant factor for the deterioration of device performance. Figure 5 shows the simulation result of electron leakage current density and the LHS electron density of EBL as a function of indium composition in the inserted InGaN.
layer, and the inset illustrates the relationship between the output power and indium composition. It is found that in LD structure with an additional 5 nm thick In$_x$Ga$_{1-x}$N inserted layer, the leakage current will be nearly completely suppressed when indium composition $x \geq 5\%$, and a too high indium composition will result in a severer electron accumulation on the LHS of EBL and more unwanted carrier recombinations. Consequently, it is reasonable to choose an optimized indium composition value to just eliminate the electron leakage, but not to bring an over-accumulation of electrons. It can be seen that the output power reaches its maximum when the indium composition equals to $\sim 5\%$, while a lower or higher indium composition will bring a larger residual electron leakage or a more serious accumulation of electrons on the LHS of EBL and then deteriorate the device performance.

![Figure 5](image.png)

Fig. 5. Electron leakage current density and left-hand side (LHS) electron density of EBL as a function of indium composition of inserted 5 nm thick InGaN layer in LDs at 100 mA. Inset shows the output power of the device versus indium composition of inserted InGaN layer. The vertical arrows show a critical indium composition value ($\sim 5\%$) at which the electron leakage is almost eliminated and the output power reaches its maximum.

Figure 6 shows the P-I-V diagrams of the reference and new LDs. As for the I-V characteristic, the threshold voltage of the two LDs is nearly the same, while their differential resistance is slightly different. It can be derived that the differential resistance varies from 14 $\Omega$ for reference LD to 17 $\Omega$ for new LD, which is probably caused by the increased EBL barrier height for electron in new LD. It is noted that in the P-I characteristics both threshold current and slope efficiency are improved remarkably, which should ascribed to the reduction of electron leakage in new LD. Actually, other factors, such as the optical confinement and free carrier absorption, do not change too much since the inserted InGaN layer is very thin and its indium composition is relatively small. In our simulation results, it is found that the optical confinement factor is 2.9\% and 3.0\% for reference LD and new LD. The loss induced by free carrier absorption is 19.45 cm$^{-1}$ and 19.40 cm$^{-1}$, respectively. These differences are small and can be nearly neglected. For reference LD, the threshold current is 54 mA, corresponding to a threshold current density value of 2.7 kA/cm$^2$, while for new LD this current is reduced to 46 mA (2.3 kA/cm$^2$), i.e., 14.8\% lower than that of reference LD. The slope efficiency is also improved from 0.92 W/A for reference LD to 1.1 W/A for new LD by 19.6\%. Then we can obtain the collection efficiency ($\eta_i$) of carriers in the active region by using the relation between the light output power ($P_{out}$) versus the injection current ($I$):

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where $I_{th}$ is the threshold current, $\hbar \omega$ is the energy of a photon, $q$ is the unit charge, $\alpha_i$ is the intrinsic loss, and $\alpha_m$ is the mirror loss. It can be derived from Eq. (1) that the collection efficiency is 74.8% and 89.4% for reference LD and new LD, respectively. The increase of collection efficiency is attributed to the reduced electron leakage current in new LD. At the same injection current of 100 mA, the output power of reference LD is 41.0 mW, while it is 58.6 mW for new LD. The corresponding wall-plug-efficiency is 8.5% and 11.6%, respectively. It is clear that the performance of new LD is obviously improved as compare to reference LD.

Fig. 6. Power-voltage-current diagrams of the reference and new InGaN-based laser diodes.

4. Conclusions

In conclusion, the role of an additional thin undoped InGaN layer prior to AlGaN EBL in suppression of electron leakage in InGaN-based blue-violet laser diodes was investigated by numerical device simulation. It is found that by inserting a thin undoped InGaN layer, the barrier height between the last QB layer and EBL is increased since the quasi Fermi level is pulled down, which leads to an efficient elimination of electron leakage. Thus, the characteristics of InGaN-based laser diodes were improved with a lower threshold current density and a higher slope efficiency.

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