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Original scientific paper

CONTROLLED ELECTRON LEAKAGE IN ELECTRON BLOCKING LAYER FREE InGaN/GaN NANOWIRE LIGHT-EMITTING DIODES

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Abstract. *In this study, we have proposed and investigated the effect of coupled quantum wells to reduce electron overflow in InGaN/GaN nanowire white color light-emitting diodes. The coupled quantum well before the active region could decrease the thermal velocity, which leads to a reduced electron mean free path. This improves the electron confinement in the active region and mitigates electron overflow in the devices. In addition, coupled quantum well after the active region utilizes the leaked electrons from the active region and contributes to the white light emission. Therefore, the output power and external quantum efficiency of the proposed nanowire LEDs are improved. Moreover, the efficiency droop was negligible up to 900 mA injection current.*

Key words: *Nanowires, Light-Emitting Diodes, Electron Blocking Layer, Molecular Beam Epitaxy.*

1. INTRODUCTION

Indium gallium nitride (InGaN) based white color light-emitting diodes (WLEDs) have tremendous energy-saving potentials in solid-state technology [2, 3]. Compared to conventional planar structures, III-nitride nanowires can exhibit significant advantages, including greatly reduced dislocation densities and polarization fields, due +to the effective lateral stress relaxation. Moreover, the nanowires show improved carrier confinement due to the incorporation of quantum dots/disks, which is promising for high-efficiency LEDs with tunable emission [4-6]. However, nanowire LEDs still pose several challenges for further improving

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the quantum efficiency and light output power, which may include non-uniform carrier distribution, electron overflow, and the presence of large densities of defects along the nanowire lateral surfaces [7, 8]. It is believed that one of the critical reasons for the efficiency droop is the electron overflow, and this also influences the output characteristics of LEDs, especially at high injection levels [9]. In LEDs, electron overflow is caused mainly by the non-uniform carrier distribution in the active region. As the effective mass of holes is higher and their mobility is lower compared to those of electrons, hole injection in InGaN/GaN structure is highly non-uniform. The holes reside close to the *p*-GaN layer, while electrons have a relatively uniform distribution in the active region. The resulted non-uniform carrier distribution throughout the active region leads to the increased electron overflow. Moreover, non-radiative recombination increases in the *p*-GaN region due to the recombination of inefficient injection of holes and leaked electrons. This further reduces the device performance. One of the solutions to reduce the electron overflow is to increase the electron confinement in the active region by introducing a high Al content *p*-AlGaN electron blocking layer (EBL) in between the last quantum barrier (QB) and *p*-GaN layer [9, 10]. However, if the EBL layer is not designed properly, it may affect the hole injection into the active region further by forming the positive sheet polarization charges at the heterointerface of last QB/EBL [11, 12] and thereby reduce the radiative recombination in the active region. In this context, designing an EBL-free LED without compromising the optical performance is highly desired.

To reduce the electron overflow without using an EBL, it is obvious that electrons should be slowed down before injecting into the active region. Inserting a layer with a lower In composition reduces the kinetic energy and velocity of the injected electrons. Moreover, by inserting this layer before the active region, hot electrons are thermalized by interacting with longitudinal optical (LO) phonons [13]. In this context, we have performed the experimental study of electron overflow in InGaN/GaN nanowire WLEDs, wherein *n*-$In_{0.2}Ga_{0.8}N$ well is incorporated between the *n*-GaN and the device active region to effectively control electron overflow. Furthermore, to utilize the electrons escaped from the active region, we have employed a *p*-InGaN quantum well between the active region and *p*-GaN to reduce the electron loss to the *p*-GaN and contribute blue light emission to relatively control the white light emission from the LED device [14, 15]. Moreover, it is required to understand the fundamental mechanism behind the reduction of electron leakage due to incorporating the coupled quantum wells, which are placed before and after the active region. In this study, we have investigated the performance of coupled quantum wells in InGaN/GaN self-organized nanowire WLEDs and presented the detailed carrier mechanism via theoretical model.

2. MOLECULAR BEAM EPITAXIAL GROWTH OF INGAN/GAN NANOWIRE HETEROSTRUCTURES ON SI (111) AND FABRICATION

Vertically aligned InGaN/GaN nanowire heterostructures were grown on Si (111) substrates by radio-frequency plasma-assisted molecular beam epitaxy (Veeco Gen II MBE) under nitrogen-rich conditions. The substrate growth temperature for GaN nanowires and InGaN are at 730 °C and 550 - 600°C, respectively. During the nanowire growth, the nitrogen flow rate and forward plasma power were kept at 1 sccm and ~ 350 W, respectively. The device active region contains ten InGaN/GaN quantum dots with ~ 3 nm InGaN quantum dot and ~ 3 nm GaN quantum barrier layer. For LED2, the device active region is sandwiched by two InGaN/GaN quantum wells which were grown at 630°C to control electron overflow in the active region and utilize the electron leakage out of the active region for the blue light emission. Such uniformly grown nanowire samples are suitable for our device fabrication. The device fabrication of WLEDs involves the following steps. To remove native oxides from the nanowire surface and the backside of the Si substrates, we have cleaned the nanowire LED samples initially with HCl and then with HF. Next, the cleaned nanowire samples were spin-coated with polyimide resist to fully cover and planarize the nanowires, which also avoids the short circuit between the top and bottom electrodes. The top portion of the nanowires were exposed by etching polyimide resist using the O_2 dry etching method. Deposition of the top metal contact (*p*-metal contact) includes three main steps. First, Ni(5 nm)/Au(5 nm) layers were deposited on the surface of *p*-GaN nanowires, followed by, deposition of 200 nm indium tin oxide (ITO) layer on the device top surface, which can serve as the current spreading layer and the transparent electrode. Further to improve the current spreading facility, Ni/Au metal patterns were deposited on the top of ITO. The *n*-metal contact was deposited with Ti(20 nm)/Au(120 nm) layers on the backside of the Si substrate. Finally, the fabricated devices were annealed at ~500°C for 1 minute in a nitrogen ambient to achieve low ohmic contact resistance. The photolithography process was deployed to define the device size and electrode position. The device area is ~300×300 μm^2. The developed phosphor-free InGaN/GaN nanowire WLEDs can be suitable candidates for smart display applications [14, 16, 17].

3. Simulation Setup and Parameters

Figure 1 shows the schematic of two InGaN/GaN nanowire LED structures considered in this study. The first structure, LED1, consists of a 200 nm *n*-GaN nanowire template, 10 multiple quantum wells (MQWs) of 3 nm InGaN quantum well (QW)/ 3 nm GaN QB in the active region, and a 100 nm *p*-GaN. The proposed structure, denoted as LED2, has the same structure as LED1, but with an extra 30 nm thick *n*-doped $In_{0.2}Ga_{0.8}N$ layer introduced in between the *n*-GaN template and the active region. Moreover, an extra 10 nm thick *p*-doped $In_{0.2}Ga_{0.8}N$ QW is also introduced in between the last barrier and *p*-GaN layer. In

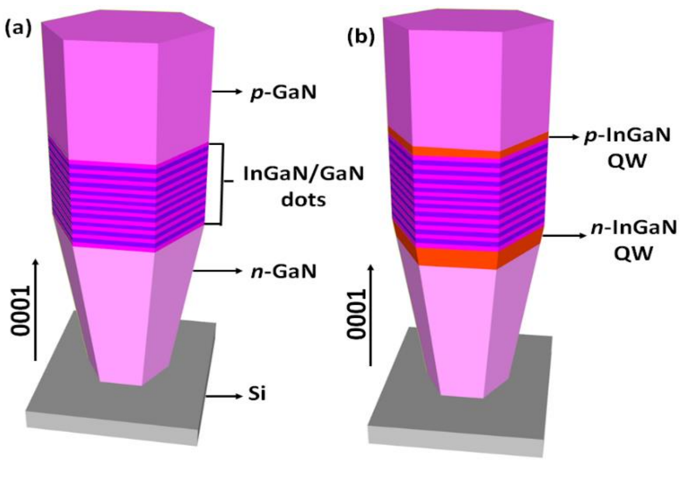

Fig. 1. Schematic diagram of (a) LED1 and (b) LED2

this study, the band offset ratio for InGaN was set as 0.7/0.3, induced polarization charges due to both spontaneous and piezoelectric polarization are assumed to be 10% of the theoretical values [18].

4. RESULTS AND DISCUSSION

Figure 2 shows the transmission electron microscope (TEM) image of LED2, where 30 nm *n*-InGaN QW, 3nm/3nm InGaN/GaN QDs in the active region, and 10 nm *p*-InGaN QW are clearly identified. Moreover, crystal defects are not visible. The InGaN/GaN QDs in the active region are positioned in the center of the nanowires due to strain-induced self-organization.

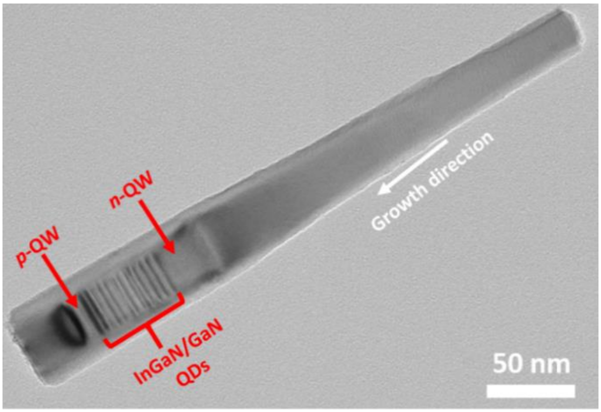

Fig. 2. TEM image of LED2, wherein *n*- and *p*- InGaN QWs and InGaN/GaN QDs are identified.

Figure 3(a) depicts a strong photoluminescence spectra of LED1 and LED2. The emission peak at ~ 550 nm corresponds to the emission from the active region, while the emission peak at ~ 430 nm in the case of LED2 is due to the emission from the coupled quantum wells. Further, normalized electroluminescence spectra of LED2 at various injection currents are shown in Fig. 3(b). The peak emission at ~ 550 nm originates from the active region, which is well agreed with the photoluminescence results, as shown in Fig. 3(a). It is seen that emission at ~ 430 nm is progressively stronger with the increase in the injection current. This is because, at a higher injection current, more injected electrons can escape from the active region and have more chance to recombine with the holes in the *p*-InGaN QW located in-between the active region and *p*-GaN layer. The electroluminescence spectra cover the whole visible range and show the balanced RGB distribution. The experimentally measured light output power (LOP) and external quantum efficiency (EQE) of LED1 and LED2 are shown in Figs. 3(c) and 3(d). It is seen that LED2 demonstrates the high output power and EQE as compared to the conventional LED i.e., LED1. More importantly, no efficiency droop was observed in LED2 up to an injection current of 900 mA. The improved performance of LED2 is attributed to the InGaN coupled quantum wells incorporated before and after the active region. The detailed mechanisms of the InGaN coupled quantum wells on the improvement of the LED performance are theoretically investigated through the mean free path (l_{MFP}) model as follows.

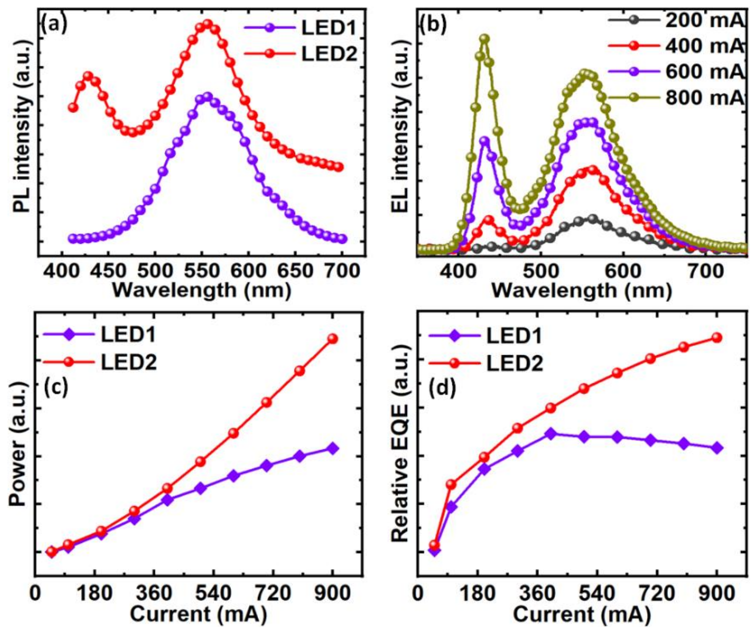

Fig. 3 (a) Normalized photoluminescence spectra of LED1 and LED2 measured at 300K, (b) Electroluminescence spectra of LED2 measured at different injection currents at 300K, (c) Light output power-current characteristics for LED1 and LED2 measured at 300K and (d) Relative EQEs measured for LED1 and LED2 measured at 300K.

The schematics of the energy band diagrams of LED1 and LED2 are depicted in Figs. 4(a) and 4(b), respectively, along with four electron transport processes in the active region. Illustrated in Fig. 4, the incoming electrons are scattered and fall into the quantum wells denoted by process 1. Some of those fallen electrons recombine with the holes radiatively as well as with the crystal defects as depicted by process 2 while remaining electrons escape from the QWs and become free again, as illustrated by process 3. In addition, some electrons with longer l_{MFP} travel to a remote position without being captured by the quantum wells as depicted by process 4. The l_{MFP} of these electrons needs to be reduced so that the carrier concentration in the QWs would be increased that would favor the higher radiative recombination rate in the active region by reducing the electron overflow. Here, we have considered the total number of electrons injected into the *n*-GaN region to be N_0 for both LED structures.

For the simplicity of the model, electron loss through non-radiative recombination is neglected. Also, the hole concentration in the *n*-InGaN layer between *n*-GaN and active region in the case of LED2 is much lower than the electron concentration, so the electron loss through radiative recombination with holes is also negligible. It is assumed that out of N_o electrons, N_2 electrons captured by the first extra QW undergo thermalization with LO phonon emission while remaining electrons denoted as N_1, directly travel over the extra QW layer without undergoing thermalization. The captured electrons in the quantum wells are correlated with the electron l_{MFP} [19]. To increase the number of the quantum well-captured electrons, the electron l_{MFP} within the InGaN/GaN MQW region must be reduced.

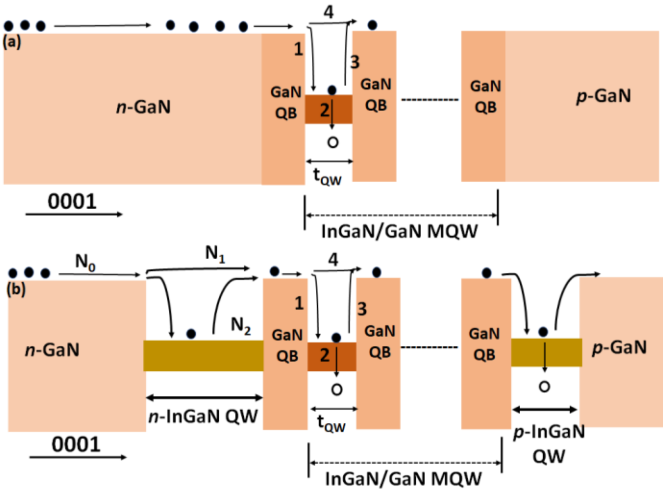

Fig. 4. Schematic energy band diagrams for (a) LED1 and (b) LED2

To understand the working mechanism of the extra QW before the active region in LED2 in reducing l_{MFP}, electron l_{MFP} in both the LEDs are calculated, which is a function of thermal velocity (v_{th}) and the scattering time (τ_{sc}) set to 0.0091ps [20, 21], as shown in Eq. 1. v_{th} can be further expressed as shown in Eq. 2. For LED2 with an extra QW n-InGaN before the active region, the expression for v_{th} will be as shown in Eq. 3.

$$l_{MFP} = v_{th} \times \tau_{sc} \quad (1)$$

$$v_{th} = \sqrt{2\times[E]/m_e} \quad (2)$$

$$v_{th\_eQW} = \sqrt{2\times[E+\Delta E_c + qV - \hbar\omega_{LO} - \Delta E_c]/m_e}$$
$$= \sqrt{2\times[E+qV-\hbar\omega_{LO}]/m_e} \quad (3)$$

In Eq. 1-3, E is the electrons energy before getting into the QW i.e., electron energy in the n-GaN layer, m_e is the effective mass of electrons. -$\hbar\omega_{Lo}$ means the energy loss by phonon emission, qV is the work done to the electrons by the polarization induced electric field in the extra QW. The first ΔE_c in Eq. 3 represents the kinetic energy received by the electrons when jumping over the conduction band offset between n-GaN and n-$In_{0.2}Ga_{0.8}N$ extra QW and $-\Delta E_c$ represents the energy loss by the electrons when climbing over the conduction band offset between n-$In_{0.2}Ga_{0.8}N$ and the GaN layer. Here it is assumed that the thermionic emission process dominates over the intra-band tunneling during the electrons transport into the active region, thus ΔE_c can be eliminated, as shown in Eq. 3. The energy loss through LO phonon emission i.e. -$\hbar\omega_{Lo}$ is considered to be 92 meV [21] and $qV = \int_0^{t_{eQW}} q \times E(y)dy$ is calculated from the electric field as shown in Fig. 5(a). Value of qV is found to be 47 meV. To understand the effect of extra QW to reduce the electron mean free path, it can be understood from Eq. 2 and 3 that $E + qV - \hbar\omega_{LO} < E$. As qV is 47 meV and $\hbar\omega_{Lo}$ is 92 meV, overall $E + qV - \hbar\omega_{LO} < E$ due to which $v_{th\_eQW} < v_{th}$ and $l_{MFP\_eQW} < l_{MFP}$. This shows that the extra quantum well before the active region has a significant effect in reducing the electron l_{MFP} in the active region, and consequently increasing capture efficiency of electrons in the quantum well and reducing the possibility of electron leakage, as shown in Fig. 5(b).

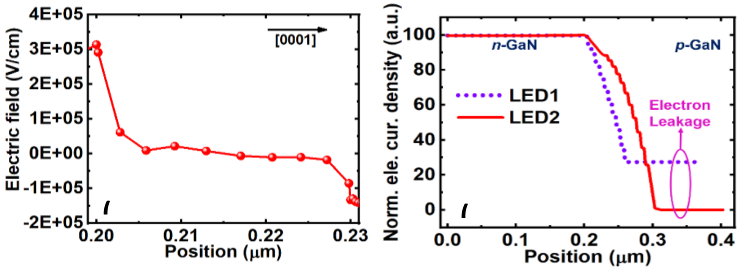

Fig. 5 Calculated electric field as a function of position within the *n*-InGaN layer at 900 mA

Further, a blue-emitting InGaN QW is incorporated between the last QB and *p*-GaN region, wherein the escaped electrons from the active region can be captured and radiatively recombined with the holes as the hole concentration in this QW is high as it is close to *p*-GaN region. This radiates blue light and contributes to the white light emission from the LED device. The resulting device exhibits highly stable white-light emission characteristics.

5. Conclusion

In conclusion, a highly efficient and truly white light-emitting InGaN/GaN nanowire LED with a coupled quantum well is demonstrated. The coupled *n*-InGaN QW incorporated between the *n*-GaN and active region improves the electron capture efficiency in the multiple quantum wells by reducing l_{MFP} after electrons undergo thermalization by phonon emission in the *n*-InGaN QW. Further, the *p*-InGaN after the active region captures the leaked electrons and contributes to the white light emission by radiatively recombine with the holes. The resulted EBL-free nanowire white LEDs show improved output power and no efficiency droop up to injection current of 900 mA.

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