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Suppression of electron overflow and efficiency droop in N-polar GaN green light emitting diodes

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In this letter, we experimentally demonstrate direct correlation between efficiency droop and carrier overflow in InGaN/GaN green light emitting diodes (LEDs). Further, we demonstrate flat external quantum efficiency curve up to 400 A/cm\(^2\) in a plasma assisted molecular beam epitaxy grown N-polar double quantum well LED without electron blocking layers. This is achieved by exploring the superior properties of reverse polarization field of N-face polarity, such as effective carrier injection and higher potential barriers against carrier overflow mechanism. The LEDs were found to operate with a low (~2.3 V) turn-on voltage. © 2012 American Institute of Physics.

GaN based light-emitting diodes (LEDs) have been commercialized for lighting and displays due to their higher efficiency and longer lifetimes compared to conventional lighting and display sources. However, a significant road-block to the realization of high-power, high-brightness applications is a reduction in emission efficiency at high injection current densities (efficiency droop).\(^1\)\(^-\)\(^3\) Efficiency droop is higher for longer wavelength emitters such as in the technologically important green wavelength region, and while the reason for this remains a topic of active research; various groups have identified it to be due to Auger recombination processes, overflow electron current, and inefficient carrier injection, and transport mechanisms.\(^4\)\(^-\)\(^6\) It has also been reported that the proposed Auger non-radiative recombination process is unlikely to be the cause for the droop since the Auger recombination coefficients are too low to account for the efficiency losses.\(^1\)\(^1\)\(^-\)\(^3\)\(^1\)\(^1\)\(^6\) The effects of electron overflow current on droop were investigated using multiple-quantum-well (MQW) active regions, Al\(_x\)Ga\(_{1-x}\)N and lattice matched InAlN electron blocking layers (EBLs), and non-polar LEDs.\(^1\)\(^,\)\(^1\)\(^2\)\(^-\)\(^1\)\(^4\) While these were shown to improve the efficiency, the use of MQWs and EBLs also degrades the carrier injection and transport mechanisms.\(^8\)\(^,\)\(^9\)\(^,\)\(^1\)\(^5\) In addition, previous reports showed that EBLs mitigate efficiency droop in non-polar devices implying that electron overflow plays an important role even in non-polar InGaN LEDs.\(^1\)\(^6\)

Most commercial LEDs are fabricated with the p-top junction oriented along the +c or (0001) direction (p on top of n on a +c oriented substrate). Reversed polarization devices can be achieved using a p-down structure on a Ga-polar substrate (n on top of p on a +c oriented substrate) or a p-up junction on a −c oriented or N-polar substrate (p on top of n on a −c oriented substrate). Simulations of reversed polarization emitters indicate several advantages over conventional emitters for device parameters such as electron overflow, injection efficiency, and laser threshold current density.\(^1\)\(^7\)\(^,\)\(^1\)\(^8\) However, there have been very few experimental reports on InGaN/GaN quantum well emitters with reverse polarization due to the inherent challenges in growth and fabrication.\(^1\)\(^9\)\(^-\)\(^2\)\(^1\) Ga-polar p-down devices have been investigated but found to be impractical due to the difficulty in obtaining low contact resistance to the etched p-type region and current crowding in resistive p-type epitaxial layers.\(^2\)\(^0\) In this letter, we investigate p-top junctions on a N-polar substrate to investigate the effects of reverse polarization in N-polar LEDs and show (i) that the efficiency droop can be correlated with electron overflow effects and (ii) that the reversal of built-in polarization fields in these N-polar LEDs can be used to mitigate electron overflow and efficiency droop at higher currents. It has also been reported that indium incorporation along N-polar InGaN is higher compared to Ga-polar crystal under similar growth conditions which sets motivation for long wavelength nitride emitters along N-polar crystal orientation.\(^2\)\(^2\)\(^,\)\(^2\)\(^3\)

Figs. 1(a) and 1(b) show the epitaxial structure and simulated band diagrams of the single quantum well (SQW) structures along Ga- and N-polarity under a forward current density of 100 A/cm\(^2\). Simulations were conducted using Silvaco Atlas using previously measured parameters for Auger recombination (\(\text{augn}(p) = 1 \times 10^{-34} \text{cm}^3/\text{s}\)),\(^2\)\(^4\) optical recombination (\(\text{copol} = 5 \times 10^{-11} \text{ cm}^3/\text{s}\)),\(^2\)\(^5\) and polarization sheet charge values.\(^2\)\(^6\) Potential barriers blocking injection of carriers into the quantum well for the Ga-polar orientation are absent in the reversed polarity (N-polar) case (Fig. 1(b)) which manifests as higher operating or biasing voltage for Ga-polar orientation (3.4 V) than for N-polar orientation (2.7 V) for achieving the same current density of 100 A/cm\(^2\). After injection into the quantum well, the electrons are accelerated towards the p-GaN region by the polarization field in the Ga-polar QW and have significant likelihood of tunneling or overflowing if no blocking layers are provided. In the N-polar case, injected electrons are confined at the n-GaN side and kept away from the n-GaN side by the polarization field-induced potential barrier in the QW. The N-polar device showed 1.37 eV potential barrier height for electrons (\(\Phi_{pn}\)) and 1.08 eV (\(\Phi_{pn}\)) for holes. Such values are limited to conduction and valence band offsets in Ga-polarity which are 0.7 and 0.26 eV for electrons and holes, respectively. Above simulations thus show that both electron and hole...
overflows are expected to be higher in a Ga-polar than in an N-polar device.

For experimental studies, LEDs based on SQW and double quantum wells (DQWs) were grown using a Veeco Gen 930 N2 plasma assisted molecular beam epitaxy (PAMBE) system equipped with elemental sources for Ga, In, Si, and Mg, and a Veeco uni-bulb N2 plasma source. The growth was carried out on commercially available N-face free-standing silicon-doped GaN templates (obtained from Lumilog) at a pressure of \( \leq 10^{-5} \) Torr. The InGaN QW growths were carried out at \( T = 570^\circ C \) (from optical pyrometer). As shown by the schematic in Figure 1(a), the growth was initiated with 50 nm of Silicon doped (\( \sim 3 \times 10^{18} \) cm\(^{-3} \)) GaN, 15 nm unintentionally doped (UID) GaN under Ga-rich conditions, followed by 2.5 nm 30% UID InGaN quantum well growth under N-rich condition. For the DQW sample, a 5 nm UID-GaN barrier was placed above the first quantum well, followed by a second 2.5 nm quantum well. Both structures were capped with 15 nm UID GaN followed by 100 nm p+ GaN (\( [\text{Mg}] \sim 2 \times 10^{19} \) cm\(^{-3} \)) and 20 nm p++ GaN (\( [\text{Mg}] \sim 8 \times 10^{19} \) cm\(^{-3} \)). Wider band-gap EBLs, commonly used for Ga- and non-polar LEDs, were not used in these LEDs.

The devices were fabricated using contact photolithography. A semi-transparent Ni/Au (4/6 nm) metal stack was evaporated to form the p-type electrode, followed by mesa isolation using Cl\(_2\)/BCl\(_3\) inductively coupled plasma (ICP)-RIE. Ti/Au (20/300 nm) was deposited for n-GaN contacts, and thick Au current spreading contacts were formed on the top p-GaN contacts. The measurements reported here were performed on-wafer (no dicing or packaging) for 250 \( \mu m \times 250 \mu m \) devices. The electro-luminescence (EL) data were obtained using Ocean Optics USB 2000 spectrometer with a coupled fiber optic cable.

The inset to Fig. 2(b) shows the current-voltage (I-V) plots of both LEDs. The devices exhibited low turn-on voltages (\( \sim 2.3 \) V) although we have not performed any fabrication or structural optimization. We attribute low turn-on voltage operation to decreased electron and hole potential barriers in N-polar devices validating our preceding simulated results. The presence of higher leakage current in the SQW device (inset to Fig. 2(b)) may be due to increase in inter-band tunneling of electrons and holes across thin N-polar active region.\(^{27,28}\) The electroluminescence (EL) spectrum of SQW and DQW LEDs (Figs. 2(a) and 2(b)) shows similar peak wavelengths in the green wavelength range under continuous wave (CW) electrical excitation. The EL emission peak shifted from 558 nm to 535 nm for SQW LED while it shifted from 565 nm to 535 nm for DQW as the current density was increased from 16 A/cm\(^2\) to 192 A/cm\(^2\). We attribute the rapid blue shift in relatively low driven current regime (\( < 50 \) A/cm\(^2\)) to the screening process of polarization charges and gradual blue shift at higher current operation to band filling effects.\(^{29,30}\) The only noticeable difference for the green emission was that the emission full-width-at-half-maximum (FWHM) of the SQW LED (\( \sim 78 \) nm) was higher than for the DQW LED (\( \sim 67 \) nm).

FIG. 1. (Color online) (a) Epitaxial structure of the SQW and DQW LEDs. (b) Simulated energy-band diagrams of Ga- and N-polar SQW LEDs at 100 A/cm\(^2\) current density.

FIG. 2. (Color online) EL spectra as a function of CW driving currents varying from 16 to 192 A/cm\(^2\) of (a) SQW LED and (b) DQW LED. The inset shows the I-V characteristics of the 200 \( \mu m \times 200 \mu m \) SQW and DQW LEDs.
The most important difference in the overall emission spectra of the two LEDs is the presence of UV emission with 385 nm peak wavelength (Fig. 2(a)) in the SQW LED when the drive current was higher than \( \sim 50 \text{ A/cm}^2 \), which was absent for the DQW case (Fig. 2(b)). Interestingly, such parasitic emission at 385 nm was observed by other groups from Ga- and non-polar MQWs with EBL incorporated LEDs, which had been attributed to radiative recombination due to overflowing (or tunneling) electrons from the active region to p-type GaN layers.\(^1\)–\(^3\) However, the DQW LED did not exhibit the 385 nm peak even at higher current densities up to 400 A/cm\(^2\) (Fig. 2(b)). Thus, it could be concluded that while one quantum well with the given thickness may be insufficient to prevent electron overflow, the insertion of a second quantum well provides an efficient built-in potential barrier to electron overflow in our N-polar device.

Fig. 3(a) shows the integrated EL intensity and normalized external-quantum-efficiency (EQE) of both SQW and DQW LEDs as a function of CW driving current. While SQW LED has the peak EQE at \( \sim 30 \text{ A/cm}^2 \) and drops gradually at higher driving currents indicating conventional efficiency droop, the DQW LED has the peak EQE at \( \sim 96 \text{ A/cm}^2 \) and drops only 7% at 192 A/cm\(^2\) CW current density, indicating low droop in efficiency. The parasitic UV peak at 385 nm and thus carrier overflow can be attributed to be the reason for efficiency droop in the SQW based LED at higher drive current densities. This is obvious from Fig. 3(b) which shows integrated EL intensity for the UV peak only (350 to 450 nm) in the left-axis and the normalized EQE for the green emission of the SQW LED in the right-axis. Both drop in the normalized EQE (green emission) and the rise in the intensity of parasitic UV peak become significant around the same current level implying that electron overflow is the reason for efficiency droop in SQW LED. This is further testified by Fig. 4, where the normalized EQE for the green emission from the DQW LED which is free from parasitic UV emission, stays flat with almost no efficiency droop till 400 A/cm\(^2\) under pulsed current conditions. We have thus, not only established the direct correlation between electron overflow and efficiency droop but also demonstrated how to overcome it by using DQW in N-face orientation.

In conclusion, the emission characteristics of N-polar SQW and DQW LEDs were investigated. The devices emitted green (\( \lambda \sim 535–550 \text{ nm} \)) light with a low turn-on voltage (\( \sim 2.3 \text{ V} \)). Relatively flat EQE curve was achieved up to 400 A/cm\(^2\) with EBL free DQW N-polar LED. We attribute low turn-on voltage and negligible efficiency droop characteristics to utilization of reversed (N-face) polarization charges for (1) elimination of potential barriers against carrier injection (outside the QW region) and (2) generation of potential barriers to confine carriers (inside the QW region). While the absolute efficiency values are still lower than the state-of-art green emitters due to non-optimized growth and fabrication, the experiment shows clearly that reversing the direction of polarization can lead to significant changes in emitter characteristics. While these results expand the current knowledge of the effects of polarization field on emitters and efficiency droop mechanism, further investigations would help to understand the phenomena better and eventually lead to improved efficiency in III-nitride emitters.

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