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Diffusion injected multi-quantum well light-emitting diode structure

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The attention towards light-emitting diode (LED) structures based on nanowires, surface plasmon coupled LEDs, and large-area high-power LEDs has been increasing for their potential in increasing the optical output power and efficiency of LEDs. In this work we demonstrate an alternative way to inject charge carriers into the active region of an LED, which is based on completely different current transport mechanism compared to conventional current injection approaches. The demonstrated structure is expected to help overcoming some of the challenges related to current injection with conventional structures. A functioning III-nitride diffusion injected light-emitting diode structure, in which the light-emitting active region is located outside the pn-junction, is realized and characterized. In this device design, the charge carriers are injected into the active region by bipolar diffusion, which could also be utilized to excite otherwise challenging to realize light-emitting structures. © 2014 AIP Publishing LLC.

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Light-emitting diode (LED) structures based on nanowires,^{1–6} surface plasmon coupled LEDs,^{7–10} and large-area high-power LEDs¹¹ have recently received increasing amount of attention as a potential way to increase the output power and efficiency of LEDs. Typically, in each of these LED structures, current transport is enabled by conventional configuration where the active region, e.g., quantum well (QW) or multi-quantum well (MQW) stack, is sandwiched between p- and n-doped regions. When the LED is biased, the current flows from the edges of the depletion region into the active region due to diffusion of majority charge carriers. However, also minority carrier diffusion may transport carriers relatively long distances and even over the active region of an LED. This decreases the efficiency of conventional MQW LEDs since it leads into leakage current.^{12,13} While this approach to organize carrier injection into the active region works well in conventional LED structures, each of the above-mentioned LED structures face challenges in efficiently organizing the charge carrier spreading and transport into the active region.

Nanowires are expected to increase the efficiency of an LED due to improved light extraction and provide more freedom in device engineering.^{3,4,6} In addition, the high crystal quality of nanowires is expected to result in a superior internal quantum efficiency (IQE) compared to that in thin films.^{2,14} One important challenge for nanowire based LED structure is that the nanowires must have contacts on both ends to enable an electrical path through the nanowire or from the shell to the core in core-shell wires. Fabricating a contact on top end of the nanowire array is a tedious process since the nanowires have to be protected and isolated before depositing the top contact. The deposited top contact would also absorb the light emitted by the nanowires. Additional challenges arise in properly doping the nanowires.

Near surface QW LEDs with plasmonic gratings also offer distinct benefits since the light emission and extraction from such structure could be enhanced by surface plasmon coupling.^{7–10} Practical challenges arise from the required short distance between the plasmon grating and the light-emitting region, which should not be more than tens of nanometers. This requirement limits the thickness of the topmost layer drastically and impairs the charge carrier injection efficiency. In addition to challenges in organizing the charge carrier transport in the structure itself, fabricating the top contact to a such LED with good current spreading is far from trivial.

In order to fabricate a conventional large area LED structure grown on insulating substrate an opening has to be etched through the p-type layer and the MQW stack before depositing the metal contacts of the device. This will result in large lateral distance between the contacts and ultimately limit the size of the active region making large-area LED structures challenging to realize. Main benefit of large-area LED structure is that it would yield improved efficiency droop behavior since the efficiency droop is shown to originate from high carrier densities in the active region.^{12,15}

We have very recently simulated and proposed an alternative current injection structure based on diffusion of carriers from a pn-junction to an active region located outside the pn-junction.^{16,17} The proposed bipolar diffusion can excite the active region endowing a possible solution for most of the above mentioned challenges. In this study we demonstrate experimentally this unconventional approach to inject carriers into the active region of LED devices. We have fabricated and characterized a III-nitride diffusion injected light-emitting diode (DILED) structure in which the active region is located below the pn-junction as schematically illustrated in Figure 1. In the fabricated DILED both p- and n-type GaN layers, thus also the pn-junction, are located above the continuous indium gallium nitride (InGaN) MQW stack. To

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FIG. 1. (a) Schematic illustration of the device structure and (b) layer structure and thicknesses. The InGaIn/GaN MQW stack is located under both p- and n-layers and thus outside the pn-junction.

compare the results with theory and explain some of the measured characteristics, we also simulated electron and hole transport in the structure.

The fabricated DILEDs, shown in Figure 1, consisted of a $3\text{ }\mu\text{m}$ thick unintentionally doped intrinsic GaN (i-GaN) buffer layer on top of which a 5 well InGaIn/GaN MQW active region was grown, followed by a 100 nm n-doped layer, a 30 nm i-GaN spacer, a p-doped aluminum gallium nitride (AlGaIn)/GaN superlattice electron blocking structure, and a 400 nm p-type GaN layer. The structure was fabricated on c-plane sapphire substrate with metal organic vapor phase epitaxy (MOVPE). The precursors for the growth were trimethyl gallium (TMG), trimethyl indium (TMI), and trimethyl aluminum (TMA). For n- and p-type doping disilane (Si_2H_6) and bis(cyclopentadienyl)magnesium (Cp_2Mg) were used, respectively. Following the MOVPE growth, the wafers were patterned with standard lithography techniques. A mesa with comb like finger extensions was etched using inductively coupled plasma reactive ion etching (ICP-RIE) for revealing the n-GaN layer and leaving the p-GaN on top of the mesa. For the results presented here the length and width of the fingers were $300\text{ }\mu\text{m}$ and $30\text{ }\mu\text{m}$, respectively. The amount of fingers was 20. Ti/Au contact for the n-type layer was deposited next to the mesa as a pad with extending fingers filling the space between the fingers of the mesa. Ni/Au/Ti/Au contact for the p-type layer was deposited on top of the mesa.

The fabricated DILED was characterized with electroluminescence (EL) measurement setup. The emitted optical power was measured with an integrating sphere attached to a spectrometer. The measurements were performed at room temperature directly from the wafer without dicing and only back side emission was measured. Measured EL emission spectra of the sample excited with 20 and 160 mA injection currents are shown in Figure 2(a). The sample emitted light with a peak wavelength of 450 nm corresponding to emission from the MQW stack. With low excitation powers, a strong yellow luminescence was observed. However, by increasing

FIG. 2. (a) Spectra of the studied DILED at injection currents of 20 mA and 160 mA measured at room temperature. The intensity of the 20 mA measurement is scaled by a factor of 10 in order to show the lineshape of the spectrum. The measured optical power as a function of input current is shown in the inset. Microscope images of the DILED with (b) low and (c) high injection current.

the input current the yellow band emission rapidly saturated and its proportion to QW emission decreased to negligible level, which can be seen from the high injection measurement. Possible causes for yellow luminescence are shallow dopants in n-GaN,^{18–20} carbon impurities in i-GaN (Refs. 21–23) or gallium vacancy complexes in i-GaN.^{20,23} When the sample was examined under a microscope during low current injection, the yellow luminescence was observed to originate from the mesa of the structure, as can be seen in microscope image shown in Figure 2(b). Thus, we assume that the yellow luminescence is most probably caused by defects in the i-GaN spacer between the p- and n-GaN. The charge carriers are injected into the i-GaN spacer as in a conventional LED structure and recombine through the defect states. Blue emission was observed to originate mostly from the fingers as seen in microscope image of the DILED during high current injection shown in Figure 2(c). Since the QWs are located far outside the pn-junction, this indicates that both electrons and holes are transported to the QWs from the same side of the active region through bipolar diffusion. Input current dependent peak shift, which is typical to conventional LEDs, was not observed within the experimented input current range. This suggests that the electric field inside the QWs is much less dependent on the external bias voltage than in conventional III-N LEDs.¹⁵ The bias voltages at 20 mA and 160 mA operating currents were

3.9 V and 5.8 V, respectively. The relatively high bias voltages are expected to be mainly caused by the unoptimized metal contacts as well as the resistance of the thin n-GaN layer of the DILED structure. Generally the I-V characteristics (not shown) of the fabricated DILEDs were comparable to conventional InGaN-GaN MQW LEDs.

The measured optical output power of the sample as a function of injection current is shown in the inset of Figure 2(a). The 250 mA injection current corresponds to current density of 40 A/cm², when the area of p-contact is considered as the area of the device. In the measurement of the optical power the defect or impurity related yellow band luminescence was discarded and only the wavelength region from 400–500 nm was taken into account. In the experimented input current range, the output power of the DILED increased superlinearly with increasing input current. This is in contrast to a conventional III-N LED structure where the efficiency droop starts to affect the light output at similar input current densities. Reasons for the exceptional behavior, i.e., no effect from efficiency droop at high injection currents is presently expected to be due to low carrier concentration in the active region caused by low injection efficiency of the unoptimized device structure.

We also compared the measurement results to simulations performed using standard current transport equations for LEDs.^{24,25} The simulated electron and hole densities at bias conditions where IQE of the studied structure is at maximum are shown in Figure 3. The hole concentration decreases as a function of depth as the holes diffuse deeper into the n-GaN. Despite the low hole concentration at the edge of the n-GaN region next to MQW stack, the MQW stack acts as a drain and both electron and hole concentrations increase drastically in the active region. Additionally just above the active region the electron concentration decreases because of the active region efficiently captures electrons from the n-GaN layer. The simulated hole concentration decreases rapidly below the active region and gradually approaches the background impurity level, leaving a

FIG. 3. Simulated hole (N_p) and electron (N_n) concentrations at maximum IQE condition and the schematic layer structure with corresponding doping levels.

thick depletion layer below the active region. Numerical simulations of the layer structure confirm that neither electron nor hole current is circulating through the i-GaN buffer layer. The hole doping level used in the simulation was $2 \times 10^{17}/\text{cm}^3$ for p-doped regions and electron doping levels were $5 \times 10^{18}/\text{cm}^3$ and $5 \times 10^{16}/\text{cm}^3$ for n-doped and non-doped regions, respectively. In order to simplify the simulation the active region was defined as one 10 nm thick QW and the electron blocking layer as a 20 nm thick p-doped AlGaIn layer.

In the presently studied DILED structure the external quantum efficiency (EQE) is fairly low. The low efficiency is also reproduced by the numerical simulations. Figure 4 shows the simulated injection efficiency η_{inj} of the structure and the measured EQE as a function of current density. Here, the injection efficiency is defined as the proportion of charge carriers recombining in the active region to total injected charge carriers. The order of magnitude difference between η_{inj} and EQE is mainly due to extraction efficiency.²⁶ The simulations indicate that η_{inj} is low mainly due to inefficient hole diffusion limited by the 30 nm thick i-GaN spacer, the 100 nm thick n-GaN, AlGaIn/GaN EBL superlattice, the uppermost GaN barrier of the MQW stack and the potential barriers due to the positive polarization charge between GaN and InGaN. Low η_{inj} for its part causes the low output powers of the device. However, η_{inj} increases throughout the whole simulated current density range and is predicted to be much higher for optimized structures.¹⁶

As seen in Figure 4, EQE increases as the input current increases, due to increasing η_{inj} as suggested by the numerical results. However, it increases more rapidly than the η_{inj} and the simulated EQE (not shown) at high current densities. We believe this to originate from improved diffusion current into the MQW stack due to increased operating temperature, which is more significant than the possible thermal degradation of IQE of the QWs. This is in stark contrast with conventional thermal behavior of LEDs.²⁴ Temperature measured from the back side of the wafer rose to 70 °C with the injection current of 250 mA due to Joule heating and non-radiative recombination. Using a simple finite elements heat transfer and natural convection model we estimated that

FIG. 4. Simulated injection efficiency η_{inj} and the measured EQE of the fabricated DILED as a function of current density.

the corresponding pn-junction and the active region temperature was approximately 80 °C. Furthermore, when the sample was cooled by a strong room temperature N₂ gas flow during high current injection, we observed a decrease in optical power. However, in order to make final conclusions on the origin of the anomalous thermal behavior of the DILED further investigation is required.

The simulated EQE (not shown) is of the same order of magnitude as the measured EQE, albeit the present model does not reproduce the rapid increase with high injection currents due to simplified thermal dependence of the model parameters. The differences could also be partly explained by the uncertainty in the ABC model parameters used in the simulations. Due to the qualitative agreement, however, we expect that the simulation tools can be used to reliably describe the basic operation of various DILED structures. As the same simulation tools have been used to show that near unity injection efficiencies are possible with bipolar diffusion injection,^{16,17} optimization of the structure should also lead to higher efficiencies. Some obvious optimization targets are the layer thicknesses and doping levels as well as reducing finger widths closer to the diffusion lengths of the carriers.

In conclusion, this work provides the experimental demonstration that bipolar diffusion can transport electrons and holes into the active region located outside the pn-junction proving that it can be utilized for electrical excitation. The thermal properties of the studied structure are quite different from conventional LED structures as the efficiency of the device increases with temperature. Also the dependence of the peak wavelength on bias present in conventional LEDs due to quantum-confined Stark effect (QCSE) is not observed. With further optimization the efficiency of the device is expected to increase considerably, possibly challenging the conventional device structures in selected applications. In particular, it would enable a new way to inject current to nanowires and near surface structures as well as fabrication of large-area devices with improved current spreading.

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