Highly Efficient GaN-based Bipolar Cascade LEDs

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Abstract – **GaN-based light-emitting diodes (LEDs) exhibit a severe efficiency droop with increasing current. The physical mechanisms behind this droop phenomenon are still under dispute, but most droop models hold the rising carrier density inside the quantum wells responsible. This paper analyses a new approach to circumvent the droop problem by raising the quantum efficiency beyond 100% utilizing multiple tunnel junctions inside the multi-quantum well active region.**

GaN-based LEDs are of major interest for applications in lighting, displays, sensing, biotechnology, medical instrumentation and other areas, but their development is handicapped by a significant efficiency reduction with increasing injection current (efficiency droop).[1] Various physical mechanisms have been proposed to explain the efficiency droop. Among them are density-activated defect recombination,[2] enhanced Auger recombination,[3] and electron leakage.[4] While all these mechanisms were identified experimentally on different LEDs, conclusive evidence is still missing that the magnitude of any mechanism is sufficiently large to single-handedly cause the efficiency droop. However, all these proposals hold the rising carrier density inside the multi-quantum well (MQW) active region responsible for increasing carrier losses that cause the efficiency droop. Therefore, a possible solution lies in the reduction of the QW carrier density required for a given output power by increasing the number of wells. But this concept is plagued by the non-uniform vertical carrier distribution commonly observed with thick InGaN MQW regions.[5] Electrons have a lower effective mass and they move more easily across the MQW than holes, leading to relevant light emission from the p-side quantum wells only. Consequently, a superior approach should be the cascading of thinner MQW regions with a tunnel junction in between, which allows for the repeated use of electrons and holes for photon generation. Such bipolar cascade (BC) devices were experimentally demonstrated for several types of light emitters, including GaAs-based lasers [6] and GaSb-based LEDs.[7] Dual-wavelength GaN-based LEDs utilized the same concept, but with two different active regions.[8] Most recently, an analytical model was proposed which predicts a significant efficiency enhancement for GaN-LEDs with up to 50 tunnel junctions,[9] but this prediction is only based on the increasing total thickness of active layers, i.e., this simple model gives the same result without tunnel junctions.[10]

Using advanced numerical device simulation,[11] we here show that significant efficiency enhancements can be achieved in BC-LEDs without changing the total number of quantum wells. Schrödinger and Poisson equations are solved iteratively in our quantum well model. The built-in polarization is adopted from a recently published second-order model.[12] The carrier transport model considers drift and diffusion of electrons and holes, Fermi statistics, thermionic emission at hetero-interfaces, as well as band-to-band tunneling based on the common WKB approximation.[13] Both Auger recombination and electron leakage are included as possible droop mechanisms. Further model details can be found elsewhere.[14]

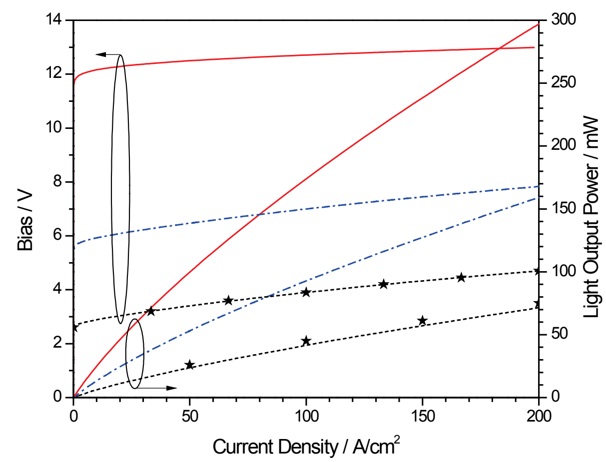

Fig. 1: LED bias and output power vs. current density: stars – measurement, lines – simulation (dash – reference device without tunnel junction, dash-dot – one tunnel junction, solid – three tunnel junctions).

For comparison and model validation, we first simulate a conventional blue LED according to published design specifications.[15] The reference device includes eight 2-nm-thick $In_{0.12}Ga_{0.88}N$ QWs separated by 15-nm-thick GaN barriers. A 45-nm-thick p-$Al_{0.15}Ga_{0.85}N$ electron blocker layer (EBL) is grown on top of the MQW, covered by a p-GaN cap layer Figure 1 demonstrates the good agreement between simulated LED performance and published measurements.

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Without changing the total number of 8 quantum wells, we now introduce a p-GaN/n-GaN tunnel junction into the MQW of the reference device, together with a p-AlGaN EBL to suppress electron leakage from each MQW set. The corresponding band diagram and photon emission profile are shown in Fig. 2. The photon generation in this BC-LED works as follows. Conduction band electrons are injected from the left-hand side, recombine within the first MQW, and then move inside the valence band toward the tunnel junction, where they are transferred into the conduction band of the second MQW stack, so that they get a second chance to generate photons. The emission profiles of each MQW set are almost identical. The total light output is significantly higher than with the reference LED but the price is paid in form of a higher bias. Figure 1 also shows results with three tunnel junctions that divide the MQW into four QW pairs.[16]

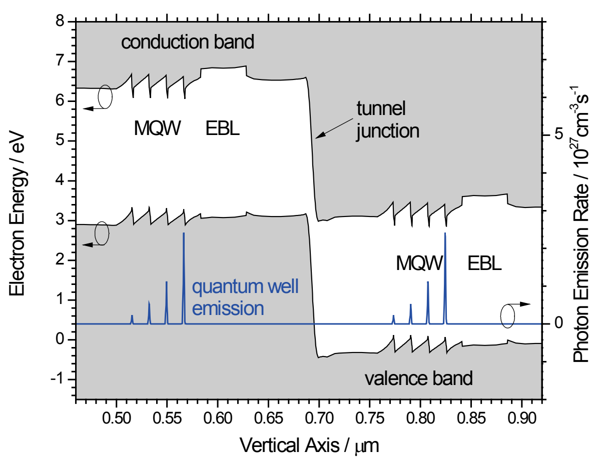

Fig. 2: Energy band diagram and photon emission rate for the LED with one tunnel junction at a current density of 200 A/cm^2.

The external quantum efficiency (EQE) is defined as ratio of the emitted number of photons to the number of injected carriers. Since three tunnel junctions give each carrier four opportunities to generate photons, the EQE could be as high as 400% without losses of carriers or photons. Carrier losses are described by the internal quantum efficiency (IQE) and photon losses by the light extraction efficiency (EXE, EQE= IQE x EXE). The extraction efficiency EXE = 80% of the reference device is hardly affected by the tunnel junctions. Using an absorption coefficient of 125/cm for the 15nm thick tunnel-junction p-GaN layer ($5x10^{19}$ cm^{-3} Mg),[17] our model predicts less than 0.1% EXE reduction for the BC-LED with three tunnel junctions. Even a 100 times stronger tunnel junction absorption would still result in EXE=75%.

The EQE efficiency characteristics simulated for our three devices are shown in Fig. 3. The EQE peaks at 63% for the reference device, at 131% with one tunnel junction and at 253% with three tunnel junctions. Note that the EQE is plotted vs. output power; plotting it vs. current density would be misleading since any given current density injected into the BC-LEDs is accompanied by higher output power than with the reference device (Fig. 1). The overall goal is to achieve high efficiency at high output power, even if the efficiency droop cannot be eliminated. The most instructive efficiency parameter is the ratio of output power to input power (wall plug efficiency, WPE). In our case with three tunnel junctions, the WPE increases to 40% at 100mW output power, compared to 17% with the reference device.[16] This WPE enhancement is due to the lower QW carrier density which leads to reduced carrier losses, as intended.

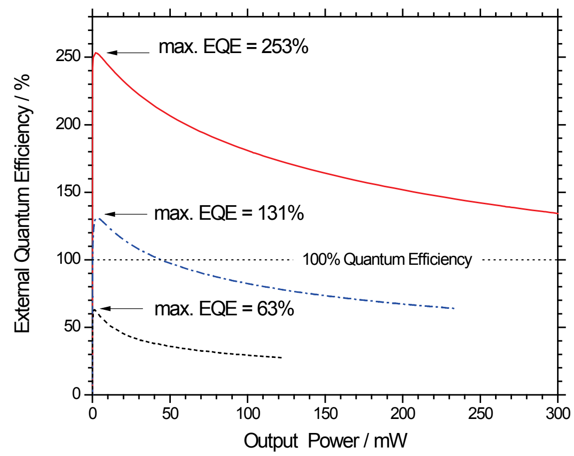

Fig. 3: LED quantum efficiency vs. output power (dash – reference device without tunnel junction, dash-dot – one tunnel junction, solid – three tunnel junctions).

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