Student Paper

Overcoming Nitride Light Emitting Diode Efficiency Droop by Tunneling Based Carrier Regeneration

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In this research we show that it is possible to cascade multiple GaN p-n junctions using visible transparent tunnel junctions with low resistance and negligible voltage drop. Based on performance parameters of current commercial LEDs, we show that the efficiency droop problem can be almost completely circumvented by using tunneling-based carrier regeneration in cascaded multiple active region LED structures.

Efficiency droop in Gallium Nitride LEDs is one of the major roadblocks against widespread adoptions in solid state lighting. In the last decade, there has been extensive work on identifying and overcoming the Nitride LED efficiency droop, [1-6] but the underlying reason is still under debate and no designs has been completely successful in solving the problem.

The efficiency droop occurs as LEDs are driven at higher currents for high optical output power. In this research, we suggest a solution to the efficiency droop problem by proposing cascaded structures where high optical output power can be obtained at low current density. To achieve this, it is required to obtain multiple radiative recombination processes from a single injected electron. This characteristic can be obtained by epitaxial cascading of light emitting diodes (LEDs) by using tunneling junctions as carrier regeneration centers.

As a demonstration for the feasibility of cascading GaN emitters, we designed an experiment to epitaxially connect multiple (1, 2, and 4) p-n junctions in series (Fig. 1) using GdN-based visible transparent tunnel junctions.[7,8] The top and bottom of this structure are both n-type since the tunnel junction eliminates the need for a top p-contact. As the p-n junction is forward biased, the tunnel junction gets reverse biased, electrons in the valence band of p^+ GaN layer of the tunnel junction tunnel into empty states available in the n^+ GaN layer, leaving behind a hole in the p^+ GaN layer (Fig. 2b). The electrons and holes regenerated at the tunnel junctions get injected into the active region which in this case is a p-n junction. In the case of a multi-quantum well active region LED, the injected hole and electron would recombine radiatively in the quantum wells.

The experimentally cascaded diode structures showed rectifying behavior (Fig. 3b). Diode turn-on voltage increased with N-repeats of the device sections, as expected (Fig. 3a). Analysis of series resistances of the 100 μm^2 devices leads to a very low resistance ~$5x10^{-4}$ Ω-cm^2 per tunnel junction. Since our experiment demonstrates the feasibility of cascading active regions, we can use the measured resistance values to model cascaded multiple active region LEDs.

To model cascaded LED structures, we combine our estimates of tunneling resistance with the experimental data from the commercial LED published elsewhere so that non-idealities of the active region are taken into account.[9] The modeled I-V curves (Fig. 4a) for the cascaded structure (N=5, 20, 50) behave as expected. The input voltage at turn-on increases with the number of junctions (Fig. 4a).

The peak wall plug efficiency (WPE) occurs at higher input power as more LEDs cascaded (Fig. 4b). The WPE of the modeled conventional LED shows 87% droop at an input power of 5 W and this value decreases as N increases (Fig.4b). For the LED with N=50, the droop is only 9.5% at the same input power which is an enhancement of ~240% in WPE compared to conventional case. The enhancement is not only due to superior external quantum efficiency, but also suppression of joule heating. Since the LED is operated at higher voltage and lower current, resistive losses are lower.

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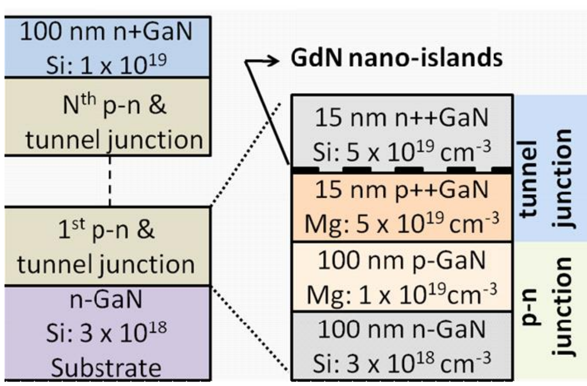


Figure 1. Epitaxial design of the cascaded p-n junctions.

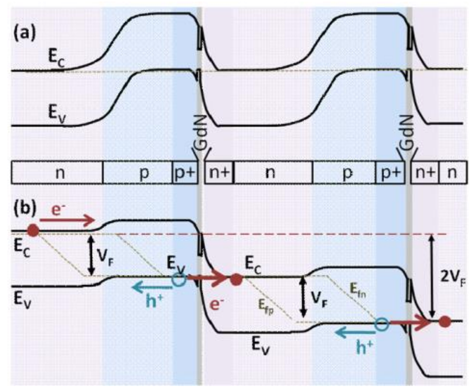


Figure 2. Energy band diagram of a cascaded p-n junction under (a) equilibrium (b) forward bias

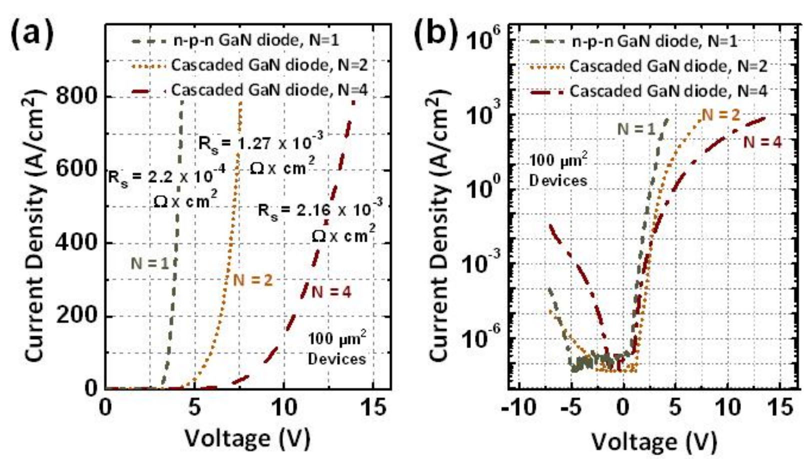
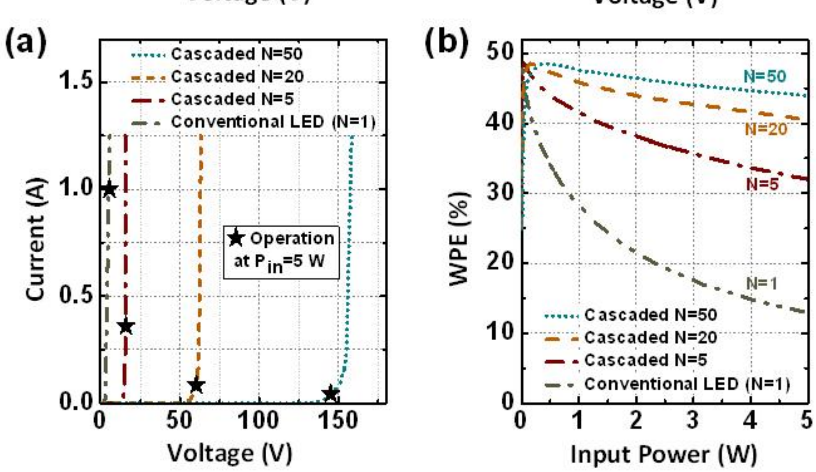


Figure 3. The experimental I-V characteristic of the cascaded p-n junctions with N=1, 3 and 4 (a) in linear scale (b)semi-log scale.



(a) I-V characteristic and (b) the change in wall plug efficiency as a function of input power of the modeled reference single junction LED and cascaded LEDs with N=5, 20 and 50.