Auctus: The Journal of Undergraduate Research and Creative Scholarship

2016

InGaN LEDs for General Lighting: Overcoming Efficiency Droop at High Current Injection

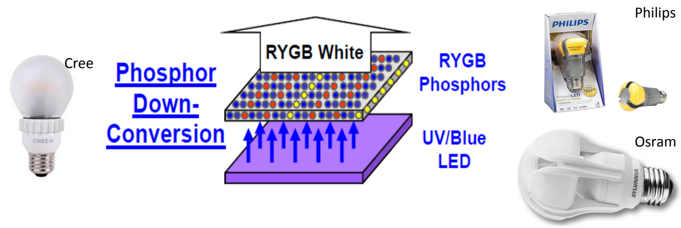
Nicolas Andrade
Virginia Commonwealth University

InGaN LEDs for General Lighting: Overcoming Efficiency Droop at High Current Injection

By Nicolas Andrade

Introduction

According to the Energy Information Administration's Annual Energy Outlook report in 2011, the United States alone consumed 97.8 quadrillion Btus (quads) of primary energy in 2010. [1] Roughly 41% of this energy was consumed for electricity use, with 18% of the electricity being dedicated to lighting. The International Energy Agency (IEA) estimated light consumption of this scale translates to CO2 production equivalent to 70% of the emissions from all of the world's light passenger vehicles. Pollution levels at this rate caused 18,200 premature deaths, 2,100,000 days of medication, and 29 million cases of lower respiratory symptoms [2].



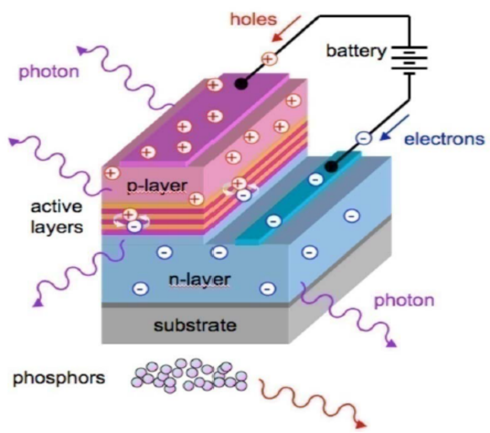
White light generation by optical pump and various commercial white LEDs.

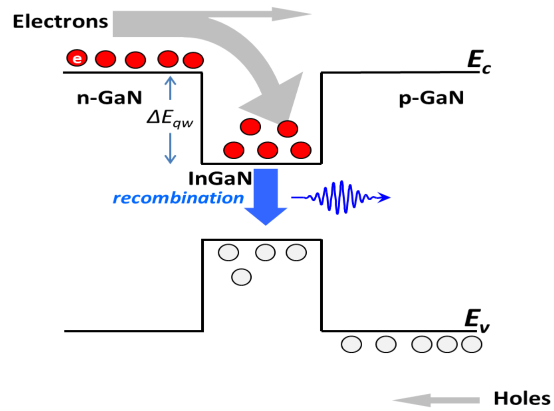
LED Background

Electrons (-) and holes (+) move through the LED due to an applied electric field (i.e. voltage bias) and recombine in the "active region", which is usually composed of quantum wells, producing the light output. Holes in the valence band are injected from the p-type gallium nitride (GaN) and electrons in the conduction band from n-type GaN into the quantum well. Blue InGaN LEDs pump yellow phosphors to produce white light. Carrier overflow occurs when an electron or a hole is not captured in the active region leading to a recombination event in the contact region without any photon emission. In InGaN materials, holes have a higher effective mass than electrons, therefore, research is concentrated primarily on reducing the efficiency droop associated with electron overflow.

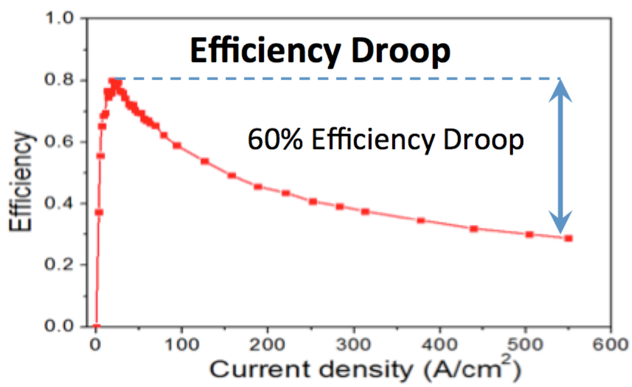
Light Source	Efficiency (%)	Efficacy (lm/W)	CRI	Lifetime (hrs)
Incandescent light bulbs	5	15	100	1,000
Compact fluorescent lamp	20	80	80-90	15,000
Long fluorescent tube	25	100	80-90	30,000
High-pressure Sodium lamp	45	130	24	1,000
White LED	50	200	90	50,000

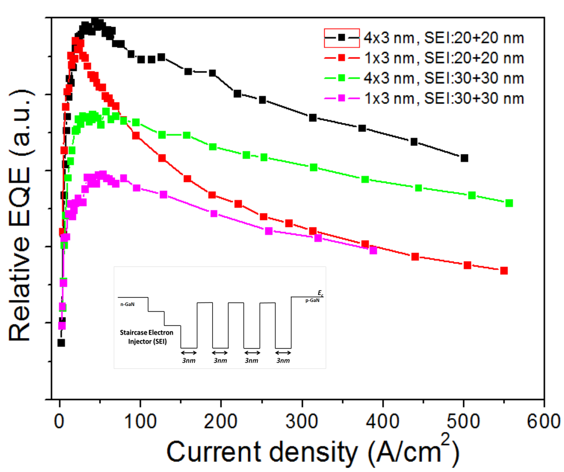
Indium gallium nitride (InGaN) LEDs provide significant energy savings in general lighting. Commercial white lighting manufacturer Cree produces an efficacy of 90(lm/W) for their 100W replacement bulb with a CRI of 80. Efficiency droop along with packaging are restrictions. [3]



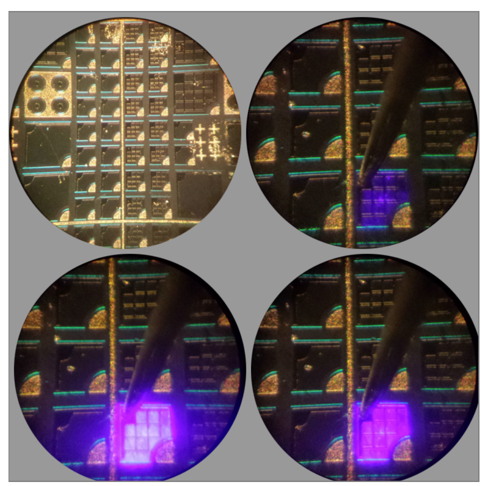


Left panel: 3D LED schematic [4]
Right panel: Energy band diagram corresponding to the LED. If an electron exists in the conduction band and a hole in the valence band of the quantum well, the two carriers will recombine to release their energy in the form of a photon.





The relative external quantum efficiency values of an InGaN LED with different staircase electron injectors (SEI). Note how the quantum efficiency decreases at high current injection.



InGaN LEDs under different current injection.
Top Left: 0A/ cm↑2
Top Right: ~5A/cm↑2
Bottom right: ~20A/cm↑2
Bottom left: ~200A/cm↑2

Current Research

As an electron enters the quantum well, it gains kinetic energy due to the band offset (ΔE_{qw}) between GaN and InGaN. This increases its velocity and the possibility of reaching the other end of the quantum well before dropping down energy levels or thermalization. In order to keep the electrons in the quantum well, and therefore increase efficiency electron blocking layers (EBL) or electron injectors have been proposed. An EBL consisting of wider bandgap aluminum gallium nitride (AlGaN) may be employed, because it produces an impassible barrier blocking electrons from leaving the quantum well and recombining in the p-GaN or contact region. The main problem associated with the EBL is that it impedes the flow of holes into the active region. The electron injectors lower the kinetic energy given to electrons because the band offset of each step is smaller. The progression through the injector sequence results in the emission of multiple longitudinal optical (LO) phonons as the electron drops down in energy, effectively "cooling" the electron. This technique is more promising than the EBL because it thermalizes the electrons slowly rather than impeding the electron and hole movement through the LED.

Conclusion

There is still significant research to be done in the area of efficiency loss in LEDs. The electron blocking layers do not appear to be the best solution for countering efficiency droop at this point due to the reduction in hole mobility. The staircase electron injector and linearly graded electron injector have problems that still need to be understood. The relevance of efficiency droop in InGaN LEDs is twofold; there is a scientific importance as well as an environmental imperative. The scientific achievement is that the improvement and understanding of efficiency droop will not only improve LED efficiency, but also allow for a better understanding of efficiency loss in similar devices such as semiconductor based lasers, photodiodes, and solar cells.

References

[1] M. Ashe, D. Chewastyk, C. Monasterio, M. Gupta, M. Pegors, "2010 U.S. Lighting Market Characterization," 2012.
[2] Health and Environment Alliance, How Coal Plants make us Sick, http://www.env-health.org.
[3] C. J. Humphreys, Solid-State Lighting, MRS Bulletin Vol. 33, pp 459-470 (2008).
[4] Courtesy of M. E. Coltrin, Sandia National Labs.