LED droop:

A critical review and novel solution

The debate over the cause of efficiency droop in nitride LEDs is heating up as recent publications 'unambiguously' assign this malady to Auger recombination. Here we take a critical look at the proposed efficiency sapping mechanisms, discuss several missing pieces in the droop puzzle and offer an intriguing new LED architecture for efficiency enhancement

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THE ERA OF SOLID-STATE LIGHTING is now upon us, with affordable LED bulbs lining the shelves of many hardware stores. Compared to the compact fluorescent, the LED bulb lasts much longer and turns on far faster, but it is yet to deliver high efficiencies due to a simple but widely disputed phenomenon: efficiency droop. Due to this mysterious malady, a doubling of the current delivers less than a doubling of the light power, causing the battalion of LEDs within the bulb to operate well below their peak efficiency, which occurs at a very low current (see Figure 1).

A fall in quantum efficiency is behind this sub-linear power increase. In an ideal world LEDs would operate at a quantum efficiency of 100 percent, with every injected electron generating a photon that is emitted from the chip. However, during the transfer of electrical to optical energy, there are always losses of electrons and photons.

To keep track of these losses, the total (external) quantum efficiency (EQE) is split up into the internal quantum efficiency (IQE) and the photon extraction efficiency (EXE). Electron (and hole) losses are widely believed to be the primary reason for efficiency droop, causing a strong reduction in IQE as the current through the LED is cranked up.

If electrons and holes don't generate photons inside the active layers (quantum wells – QWs), then what do they do? Well, there are a few other options for these carriers. In addition to the radiative recombination inside the QWs that leads to the generation of light, the electrons and holes can: undergo crystal-defect-related recombination inside the QWs; Auger recombination inside the QWs; and recombination outside the QWs, caused by electron leakage from the QWs (see Figure 2).

Adding up these contributions produces a simple, popular model, where the total recombination rate is given by $R = An + Bn^2 + Cn^3 + Dn^4$. In this model, n is the carrier density, while the linear, quadratic, cubic and quartic terms of n are related to crystal defect related recombination, radiative recombination, Auger recombination, and recombination caused by electron leakage, respectively. Note, however, that the leakage contribution term is often ignored.

If you remember your algebra classes, you may realize that by simply manipulating the *A*, *B*, *C* and *D* coefficients, it is possible to fit many different characteristics with such a formula – and it has been shown that different *ABC*(*D*) parameter sets can lead to almost identical results.

More detailed models further undermine the merit of this approach, by showing that for each of the four recombination mechanisms these coefficients are not constant, but change with carrier density. Thus, it is quite risky to draw final conclusions on the leading non-radiative mechanisms from such a simple *ABC(D)* model – especially since the quantum well carrier density is usually unknown.

It is only direct measurements that can provide the final proof for the dominating droop mechanism. Electron leakage was first observed in ultraviolet LEDs [Zhang 2008] by measuring

the light emission from *p*-doped layers, which can only produce radiative recombination when electrons travel beyond the QWs (see Figure 2). A few similar reports followed, but none could demonstrate that the magnitude of leakage fully explains the magnitude of the efficiency droop.

In fact, I am puzzled as to why there have been fewer than ten direct measurements of electron leakage published – far less than the hundreds of papers claiming that leakage is the main reason for the efficiency droop in a particular device. It is my view that authors, reviewers, and editors should pay more attention to the experimental validation of such claims. If leakage is indeed the only culprit, it is hard to fathom why none of the many experimental LED device designs have been able to eliminate droop.

Direct evidence for Auger recombination

The first direct evidence for QW Auger recombination only appeared in 2013, with two different groups employing somewhat contradicting methods. The first reported work came from a partnership between scientists at UCSB and CNRS, France, and involved measurements of high-energy (hot) electrons emitted from the surface layer of an LED [Iveland 2013]. The authors attribute these hot electrons to the QW Auger process. They argue that electron-hole recombination is facilitated by transferring the excess energy to a second electron, which becomes 'hot' and can travel to the LED surface.

However, Monte-Carlo simulations of this electron transport by other researchers from Boston University and Politecnico de Torino, Italy, indicate that the Auger-electron cannot maintain its high energy over the distance between the quantum wells and the LED surface [Bertazzi 2013].

In contrast, a very short travel distance for hot Auger electrons is assumed in the second piece of direct evidence for Auger recombination published in 2013 [Binder 2013]. In that work by researchers at Osram Opto Semiconductors, hot Auger electrons are assumed to lose their energy quickly, so that some are captured by a neighbouring quantum well. However, numerical simulations of this experiment show similar results without Auger recombination [Hader 2014].

Even if one accepts that both experiments provide proof of relevant QW Auger recombination, despite conflicting assumptions, none of them presents direct evidence that the Auger process is strong enough to single-handedly cause the measured efficiency droop.

By assigning droop solely to Auger recombination, another question crops up, which I keep puzzling over: If Auger recombination really is the only reason for the efficiency droop, why do we need an AlGaN electron blocker layer (EBL)? After all, the EBL energy barrier is not high enough to stop hot electrons generated by the Auger process.

Defects may also play a role in droop. No one disputes the influence of defect-related recombination on the LED efficiency,

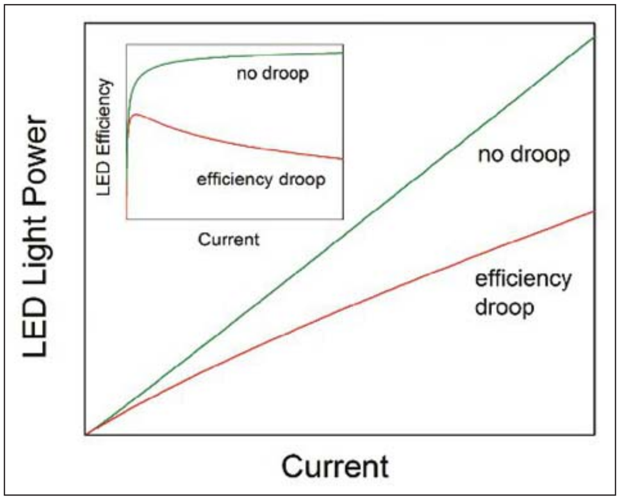

Fig. 1: Sub-linear LED light power characteristic related to efficiency droop, as shown in the inset (red curves). For comparison, the ideal of linear power without droop is plotted in green.

but this only dominates at low current or in non-commercial LEDs that are riddled with defects. Some researchers [Lin 2012] measured the efficiency droop of brighter and darker regions of a single LED separately, identifying less droop in the darker regions, accompanied by lower absolute efficiency. Such droop reduction is not desirable as the main quest is for high efficiency.

Gold Rush

The continuing ambiguity concerning the origin of LED droop has triggered a 'gold rush' in worldwide research in this topic, culminating in an ever-growing number of papers that often contradict each other. A confusing range of efficiency droop observations and explanations are resulting from varying LED fabrication and measurement conditions, and from the application of diverse models and parameters.

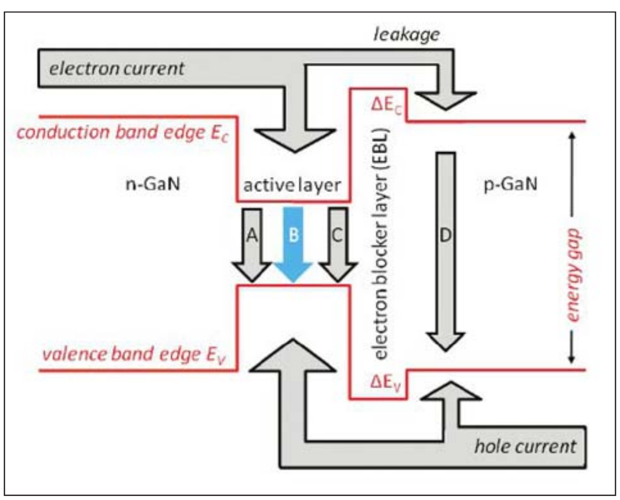

Fig. 2: Schematic illustration of the LED energy band diagram (red) with electron and hole current components. Light is generated inside the active layer which typically comprises multiple quantum wells (QWs). The four possible options for electron-hole recombination are labelled *A-D* (*A* - defect-related recombination, *B* – radiative recombination, *C* – Auger recombination, *D* – recombination outside the active layers).

Note that the employed mathematical models are based on different physical concepts – yet several of them reproduce the same type of measured efficiency characteristics. That should set some alarm bells ringing, because if dissimilar models can quantitatively explain the same experiment, then most of these models must be wrong. This dilemma represents a great challenge – but also a great opportunity to come together and work it out (see "How can we end the debate on droop?"). Let's now look at some of these advanced droop models in more detail.

Defect-related recombination is unable to cause efficiency droop if one applies the simple *ABCD* formula, because the linear term (*An*) does not increase faster with the carrier density than the light emission (Bn^2). To account for droop, the *A* coefficient itself must instead rise with the density in a super-linear way, which means that the defect-related carrier lifetime needs to decrease rapidly with higher carrier density.

How is that possible? Well, in 2007 Andreas Hangleiter from the Technical University of Braunschweig and collaborators proposed the idea that some QW recombination centres are located on an energy 'mountain', and they can only be reached after the QW 'flatland' is filled up with carriers.

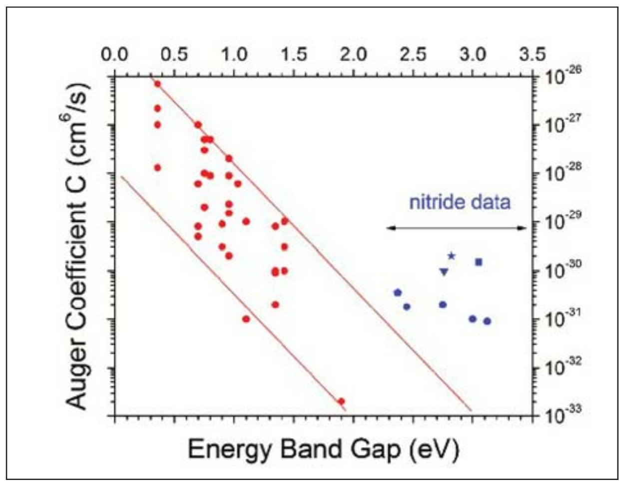

Fig. 3: Reported Auger coefficients for various semiconductors with different energy band gap scatter widely for the same material. The nitride data (blue) contradict the expected steep decline with larger band gap (red lines).

Later on, Hader and co-workers put this idea into a numerical model, described as 'density activated defect recombination' or DADR. One strength of the DADR model is that it shows good agreement with IQE measurements at low currents, all the way down to very low temperatures. However, it fails to reproduce the efficiency droop measured at higher currents. The same is true for a band tail localization model developed by Sergey Karpov from St. Petersburg and a droop model based on the influence of QW barrier states, which was proposed by Weng Chow from Sandia National Laboratories. In other words, all these models need to include Auger recombination or electron leakage to fully reproduce droop measurements.

What about Auger models?

Auger recombination is typically identified as the droop mechanism using a simple *ABC* fit. However, this approach is flawed, since the Cn^3 term in the *ABC* formula is the only term rising faster with carrier density than the light emission (Bn^2), so any *ABC* fit of the measured efficiency droop will result in a large *C*-parameter, no matter what the real cause of the droop is. For instance, if leakage is to blame for droop, Auger recombination would be wrongly identified with this approach. Moving to an *ABCD* model does not fix this issue, because this would assign part of the leakage to the *C*-parameter.

Such indirect measurements of the Auger coefficient have always been controversial. Plotting the *C*-parameter as a function of the energy band gap of various semiconductor materials shows both the steep decline in Auger coefficient with increasing band gap, and the uncertainty in values of several orders of magnitude (see Figure 3). What's more, data for nitride materials are clearly outside the broad band predicted, and this has caused great scepticism towards the Auger model for the efficiency droop.

To try and get to the bottom of whether Auger recombination is able to cause droop, several groups have been working on quite sophisticated calculations for the *C* coefficient. The direct Auger process – involving only three carriers – was initially determined to be very weak. Indirect Auger recombination was then proposed as a possible explanation, with calculations considering electron-phonon coupling and alloy scattering. However, even then the calculated indirect Auger coefficients are still below the values required to fully explain the efficiency droop, and they are only obtained for bulk layers.

This is by no means the end of the story for Auger-related droop models, though. When Marcus Deppner and colleagues from the University of Kassel included Auger electron leakage in the LED model, this appeared to enable relevant levels of droop to occur with lower Auger parameters. And somewhat surprisingly, some recent studies suggest that direct QW Auger recombination may still be to blame: The team from Boston University and Politecnico de Torino, Italy, calculates that Auger recombination strongly depends on QW width and composition; while Roman Vaxenburg from Technion, Israel, and co-workers are arguing that the electric field in the QW can exert a large influence on the Auger recombination. I believe that we should wait for some consolidation of all these different models before fundamental physics is claimed to validate Auger recombination as possibly dominating the efficiency droop mechanism.

Leaky wells?

Another popular model for LED droop, electron leakage into *p*-doped layers, tends to attribute the decline in efficiency at higher drive currents to thermionic emission from the QWs. However, it has also been argued that leakage results from hot electrons or tunnelling from the QWs.

Simulations of electron leakage are commonly based on a numerical drift-diffusion model. The leaking electrons recombine with holes in the *p*-doped layers before those holes reach the active layers (see Figure 2). Obviously, electron leakage and reduced hole injection are two sides of the same process – and not two different mechanisms. What's more, it appears that the low hole conductivity in *p*-doped GaN is actually the main reason for the electron leakage.

I have looked into this with Simon Li from Crosslight Software [Piprek 2013]. We have found that the magnitude of the electron leakage is extremely sensitive to properties of the electron blocker layer (EBL), such as the built-in polarization and the EBL band offset ratio (see Figure 4). Unfortunately, both material parameters are not exactly known. On top of this, the magnesium doping creates even more uncertainty in leakage simulations, since only a small and unknown fraction of magnesium atoms form AlGaN acceptors. For these reasons, almost all of the many published simulation studies on EBL design and optimization are quite speculative, as long as the leakage current is not validated experimentally.

How can we end the debate on droop?

THE DEBATE on the cause of droop has now been going on for the best part of ten years and various camps still seem entrenched in their contradicting positions. One obstacle to a consensus is that none of the droop models covers all possible mechanisms in sufficient detail. Complicating matters even more, the analysis of different LED designs and fabrication technologies may lead to different results. It would therefore be desirable to apply each model to exactly the same LED structure, reproduce the same LED measurements, and compare in detail all model assumptions, parameters, and results. But for understandable reasons, the LED industry is very secretive about the specifics of their device structures, while public research projects at universities often fall short of producing high-quality devices. So, dear reader, would you be able to contribute the needed details on an industry-quality LED ? If so, please send an e-mail to piprek(at)nusod.org. I will gladly forward such information to the different modelling groups to foster a consensus on the cause of the LED efficiency droop. The annual conference on "Numerical Simulation of Optoelectronic Devices" could provide a forum to discuss the results of such joint modelling effort (www.nusod.org)

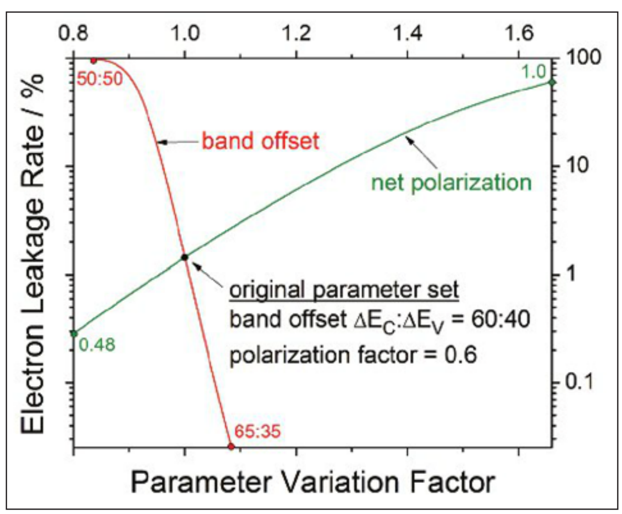

Fig. 4: The calculated electron leakage is extremely sensitive to variations of band offset (red) and net polarization (green) of the electron blocker layer (see Figure 2).

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A Novel Solution

Although those debating droop can't agree on its cause, most believe that the efficiency reduction is triggered by the rise in QW carrier density. Now, is it possible to lower the carrier density without losing light power? One seemingly obvious answer is to increase the number of QWs, but this approach is handicapped by the strong carrier accumulation on the *p*-side of the active region.

Another approach is to insert tunnel junctions into the multi-quantum well active region [Piprek 2014]. Thanks to carrier recycling by the tunnel junction, repeated use of electrons and holes for photon generation inside the QWs is then possible.

Using advanced device simulation, the performance of a design with three tunnel junctions that separate four pairs of QWs has been calculated (see Figure 5). In this case, each electron has four chances to generate a photon. If there were no losses, the quantum efficiency could be as high as 400 percent. But there is a price to pay for such an astronomical EQE: A four-fold hike in the bias required to operate the LED.

To assess the performance of this novel LED architecture, plots of the light output power as a function of the electrical input power have been simulated for three different designs with the same total active layer thickness (see Figure 6).

These calculations show that the tunnel junction design delivers twice the output power of a conventional LED – and therefore double the wall-plug efficiency – and it also outperforms the alternative approach of merging all QWs into one thick active layer (a double-heterostructure LED). However, even with the tunnel junctions, a large efficiency droop still remains – and the debate over what causes it is unlikely to go away anytime soon.

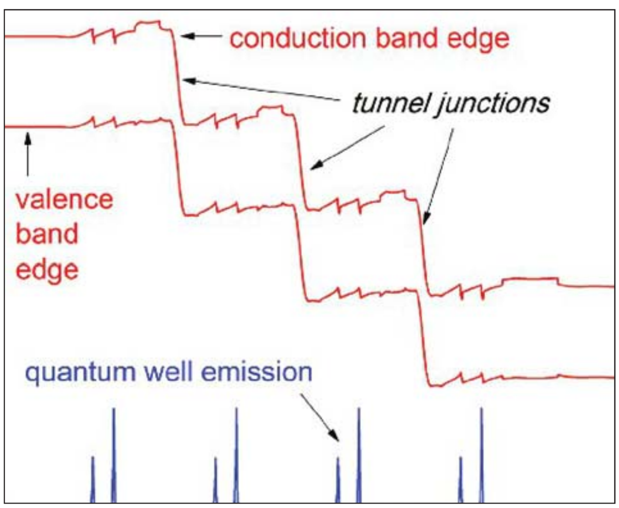

Fig. 5: Energy band diagram (red) and photon emission profile (blue) of the proposed tunnel-junction LED.

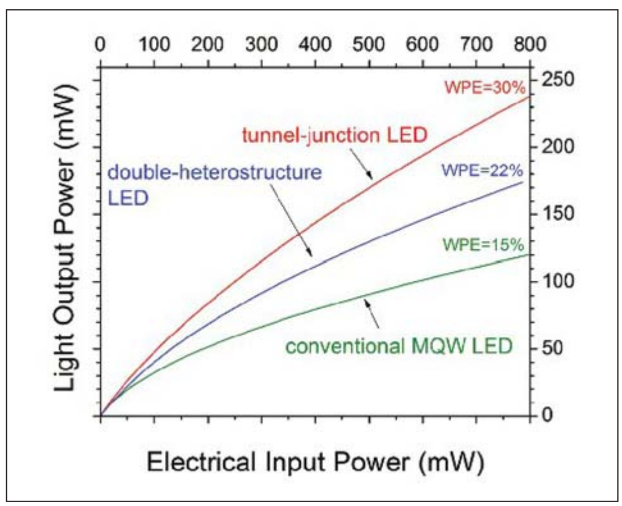

Fig. 6: Performance comparison between different LED design concepts (WPE – wall plug efficiency, numbers given for an 800 mW input power).

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